VIDEO DATA COLLECTION METHOD FOR PEDESTRIAN MOVEMENT VARIABLES & DEVELOPMENT OF A PEDESTRIAN SPATIAL PARAMETERS SIMULATION MODEL FOR RAILWAY STATION ENVIRONMENTS

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DECLARATION

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by the Stellenbosch University will not infringe upon any third party rights and that I have not previously, in its entirety or in part, submitted it for obtaining any qualification.

The processes undertaken in this study has been conducted in accordance with the "*Framework Policy for the Assurance and Promotion of Ethically Accountable Research at Stellenbosch University*" dated 20 March 2009 (University of Stellenbosch 2009) and particular attention has been paid towards complying with "*Section B1: Research Involving Human Participants*" during the survey phase of this study.

The text within this study uses terms such as "*Black*", "*Coloured*", "*Asian*" and "*White*". The use of these terms does not imply any acceptance of the racist assumptions on which these labels were based during the apartheid[1] era. The terms are used to reflect the differential manner in which apartheid impacted (and still does) on the lives of South Africans. They are used as a gross proxy measure of social groupings in South Africa. The term "*Coloured*" refers to a heterogenous ethnic group who possess ancestry from Europe, various Khoisan and Bantu tribes of Southern Africa, West Africa, Indonesia, Madagascar, Malaya, India, Mozambique, Mauritius, and Saint Helena. The extensive combining of these diverse heritages in the Western Cape has developed into a distinctive 'Cape Coloured' and affiliated Cape Malay culture.

The contents of this study reflect the views of the author who is responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies of the University of Stellenbosch. This study does not constitute a standard, specification or regulation.

Cover illustration: Courtesy PTV AG/ Global (Transportation Planning Traffic Engineering software website)

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“*Simplicity is the ultimate sophistication*” - Leonardo da Vinci (1452-1519)

ABSTRACT

The design of railway station environments in South Africa and to a certain extent internationally, is based on rules of thumb. These rules, using general macroscopic principles for determining peak passenger loads are inadequate and misleading for detailed design purposes. The principles advocated in local design guideline documents are erroneous and ignore the highly variable flow nature or "*micro-peaking*" effects that typically occur within railway station environments.

Furthermore, there are no procedures proposed in these guideline documents, which leads to ambiguous assessment techniques used by practitioners in the determination of pedestrian spatial areas. It is evident that the knowledge in the area of pedestrian movement contained within the design guidance is far from comprehensive.

Without a reliable method for estimating pedestrian levels-of-service and capacities, design of new facilities does not follow a uniform process, resulting in high levels of uncertainty in determining if the time, money and resources invested in upgrading facilities will actually cater to the demand.

The situation is further exacerbated by current industry thinking towards pedestrian modelling in South Africa, where it is perceived by both clients and practitioners to be more cost effective to use macroscopic techniques and designing infrastructure according to a "*one-level-up*" level-of-service method. Working with architects confirmed that the area of circulation design was lacking in data and guidance and that associated quantified assessments of pedestrian movement was rarely, if ever, carried out.

Towards addressing these issues, the development of a Spatial Parameter (SP)-model spreadsheet application became the main objective of the study. The model contributes towards addressing the needs of individual station users based on the trade-off between level-of-service and infrastructure costs. The output of the model allows the designer to avoid the under-provision (detrimental to operations) and oversizing of railway station infrastructure (with obvious financial implications).

The author recognised the lack of pedestrian movement data in South Africa and addressed this by conducting extensive video-based pedestrian observations aimed at exploring the macroscopic fundamental relationships and the ways in which these relationships might be influenced by the various personal, situational and environmental factors that characterise the context in which pedestrians move.

The movement trajectories of 24,410 pedestrians were investigated over three infrastructure environments at Maitland and Bonteheuwel stations in Cape Town, carefully selected to incorporate the cultural diversity common in South Africa. Tracking of pedestrians was achieved via the use of an in-house developed "*video annotator*" software tool.

Boarding and alighting rates of 7,426 passengers were also observed at these stations incorporating contributory attributes such as age, gender, body size, encumbrance, group size, time of day, and location.

The research makes a number of significant advances in the understanding of pedestrian flow behaviour within railway station environments and provides recommendations to industry of what issues to consider. The empirical study has provided comprehensive pedestrian movement characteristics incorporating the relationships between density, speed and flow including the effect of culture and other context factors unique to the local South African environment.

New methods for determining spatial requirements are proposed, together with new and unique empirical data for use by the local industry. A calibrated spreadsheet SP-model for assessing the design of concourse type railway stations is developed and presented in the study. The advance in local pedestrian flow knowledge, together with the SP-model, is shown to be practical through application to two real railway station case study projects.

The results of this study constitute an important contribution to local pedestrian flow knowledge and is considered a valuable resource for those developing pedestrian models in practice. It is expected that the results will be useful in the planning and design of pedestrian environments in South African railway stations and can be applied to other African metro railway stations with similar pedestrian characteristics.

Overall, this research has succeeded in advancing the approach to railway station design, empirical data, knowledge and methods held within the local engineering industry. However, the contribution of this study and associated conference papers is an early step in changing the perceptions in this country towards ensuring fully informed and appropriate performance-based spatial designs.

SAMEVATTING

Die ontwerp van areas binne Suid-Afrikaanse spoorweg stasies en ook tot ‘n sekere mate internasionaal, is gebaseer op historiese ondervindings asook riglyne wat tans in die praktyk gebruik word. Die riglyne gebruik algemene makroskopiese beginsels om die spits passasiersvrag te bepaal vir gedetaileerde ontwerp doeleindes. Hierdie riglyne is egter ongeskik en misleidend aangesien dit nie die hoogs wispelturige natuur van vloei en mikrospits effekte wat binne die stasies plaasvind, in ag nie.

Die riglyne ontbreek ook van prosedures wat gevolg moet word vir die bepaling van ruimtelike areas vir voetgangers wat die gevolg het dat dubbelsinnige beramingstegnieke deur praktisyne gebruik word. Die kennis oor voetganger bewegings in die ontwerp riglyne is nie omvattend genoeg nie.

Sonder ‘n betroubare beramings metode vir die bepaling van voetganger diensvlak en kapasiteit kan daar nie bepaal word of die tyd, geld en hulpbronne wat in die fasilitieit geinvesteer word, aan die behoeftes gaan voldoen nie.

Die situasie word verder vererger deur die huidige persepsie oor voetganger modellering in Suid-Afrika, waar dit deur beide kliënte en praktisyne, as ‘n meer koste effektiewe oplossing gesien word om makroskopiese tegnieke te gebruik en om infrastruktuur te ontwerp volgens ‘n metode waar ‘n hoër diensvlak as die teiken diensvlak gebruik word. In samewerking met argitekte is dit bevestig dat die area van sirkulasie ontwerp ‘n tekort het aan data en riglyne en dat die kwantitatiewe skattings verbonde aan voetganger beweging selde, indien ooit, uitgevoer word.

Die ontwikkeling van ‘n Spatial Parameters (SP)-model om die bogenoemde problem te oorkom, is die hoofdoel van hierdie tesis. Die model poog om die behoeftes van individuele stasie gebruikers aan te spreek gebaseer op die wisselwerking tussen diensvlak en infrastruktuur kostes. Die uitsette van die model stel die ontwerper in staat om ondervoorsiening en oorvoorsiening van spoorweg stasie infrastruktuur te voorkom wat nadelige vir die bedryf is en ook ooglopende finansiële implikasies tot gevolg het.

Die skrywer het die tekort aan data aangaande voetganger bewegings in Suid-Afrika geidentifiseer en dit aangespreek deur omvattende video gebaseerde voetganger waarnemings te maak met die doel om die basiese makroskopiese verhoudings te ondersoek asook in hoe ‘n mate hierdie verhoudings beinvloed word deur verskeie persoonlike, liggings- en omgewingsfaktore wat die konteks waarin voetgangers beweeg, karakteriseer.

Die bewegingsprofiel van 24,410 voetgangers is ondersoek by drie infrastruktuur omgewings by Maitland en Bonteheuwel stasies in Kaapstad. Die stasies is noukeurig uitgesoek om Suid-Afrika se kulturele diversiteit te verteenwoordig. Die voetgangers is nagevolg deur gebruik te maak van ‘n selfontwikkelde video-annoteerder sagteware.

Waarneming van die opklim- en afklimspoed van 7,426 passasiers is gemaak by hierdie stasies en faktore soos ouderdom, geslag, liggaamsgrootte, mobiliteit, grootte van groepe, tyd van die dag en ligging was ingesluit by die waarnemings.

Hierdie navorsing maak belangrike bydraes tot die begrip van die vloei van voetgangers binne spoorweg stasies en aanbevellings word aan die industrie gemaak oor die faktore wat in ag geneem moet word by ontwerp van fasilitieite. Die empiriese studie het omvattende voetganger beweging karakteristieke uitgewys wat die verhoudings tussen digtheid, spoed en vloei inkorporeer asook die effek van kultuur en ander faktore wat verband hou met die unieke konteks van die plaaslike Suid-Afrikaanse omgewing.

Nuwe metodes om ruimtelike-vereistes te bepaal word voorgestel, saam met nuwe en unieke empiriese data vir gebruik deur die plaaslike industrie. ‘n Gekalibreerde en gevalideerde SP-model is ontwikkel om die ontwerp van spoorweg stasies te assesseer en word in hierdie tesis beskyf en aangebied. Die studie toon dat akkurate data en kennis oor plaaslike voetganger vloei met die SP-model verkry kan word, soos bewys uit twee spoorweg stasie studiegevalle.

Die resultate van hierdie tesis dien as ‘n belangrike bydrae tot die kennis van plaaslike voetganger vloei en word geag as ‘n waardevolle hulpbron vir die ontwikkeling van voetganger modelle in die praktyk. Hierdie resultate mag nuttig wees gedurende die beplanning en ontwerp van voetganger-areas in Suid-Afrikaanse spoorweg stasies. Dit kan ook toegepas word vir spoorweg stasies in die res van Afrika wat soortgelyke voetganger karaktereienskappe het.

Die navorsing het daarin geslaag om die benadering tot spoorweg stasie ontwerp te verbeter, asook om empiriese data, kennis en die metodes wat binne die plaaslike ingenieurs industrie voorgehou word, te verbeter. Let egter daarop dat die bydrae wat hierdie tesis maak, asook bydraes deur relevante konferensie verhandelinge, ‘n vroeë stap is in die verandering van persepsies in Suid-Afrika om geskikte prestasie-gebaseerde ruimte ontwerpe te verseker.

BIOGRAPHY

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- Herrmann, R. and Hermant, L.F.L. (2009). *Pedestrian Modelling in South Africa: A Recent Case Study*. South African Transportation Convention, In Proceedings of the 28th Annual Southern African Transport Conference (SATC 2009), Pretoria, South Africa, Pretoria, 6 to 9 July 2009.

- Hermant, L.F.L. (2009). *Development of a SP-model towards the Macroscopic Assessment of Railway Stations in South Africa*. In Proceedings of the 28th Annual Southern African Transport Conference (SATC 2009), Pretoria, South Africa, Pretoria, 6 to 9 July 2009.

- Hermant, L.F.L., Ahuja, S., Ahuja, R. and Soper, M. (2009). *Applying Innovative VISSIM Microscopic Modelling Techniques towards Assessing Railway Station Designs in Cape Town, South Africa*. VISSM Users Group Conference, Imperial College of London, UK, July 2009.

- Hermant, L.F.L., Ahuja, R., De Gersigny, M., Emeran, H. and Herrmann, R. (2010). *Applying Microscopic Modelling and Virtual Reality Pedestrian Flow Simulation to Public Transport Interchange Design Evaluation in Durban, South Africa*. In Proceedings of the 3rd International Conference, Transport Science and Technology Congress (Transtec 2010), New Delhi, India, 4 to 7 April 2010.

- Hermant, L.F.L., De Gersigny, M. and Ahuja, R. (2010). *Innovative Methods for Assessment of Pedestrian Space Requirements for Railway Stations in South Africa*. In Proceedings of the 12th World Conference on Transport Research (WCTR), Lisbon, Portugal, 11 to 15 July 2010.

- Hermant, L.F.L. and De Gersigny, M. (2010). *Microscopic Assessment of Pedestrian Space Requirements within Railway Stations in South Africa*. In Proceedings of the 29th Annual Southern African Transport Conference (SATC 2010), Pretoria, South Africa, 9 to 12 August 2010.

- Hermant, L.F.L., De Gersigny, M., Herrmann, R. and Ahuja, R. (2010). *Applying Microscopic Pedestrian Simulation to the Design Assessment of Various Railway Stations in South Africa.* In Proceedings of the 29th Annual Southern African Transport Conference (SATC 2010), Pretoria, South Africa, 9 to 12 August 2010.

- Hermant, L.F.L. (2011). *Human Movement Behaviour in South African Railway Stations: Implications for Design*. In Proceedings of the 30th Annual Southern African Transport Conference (SATC 2011), Pretoria, South Africa, 11 to 14 July 2011.

- Hermant, L.F.L. and Ahuja, R. (2011). *Applying Innovative VISSIM Microscopic Modelling Techniques and Virtual Reality Pedestrian Flow Simulation towards Railway Station Design Evaluation in Durban, South Africa*. 21st PTV Vision Users Group Conference, New York City, 13 to 14 September 2011.

Magazine Articles:

- Hermant, L.F.L. (2002). *Challenges of Chapmans Peak Drive from a Traffic Engineering Perspective*. South African Institute of Civil Engineering Magazine, September 2002 edition.

- Hermant, L.F.L., Scott, I. and Cronje, P. (2009). *Taking Pedestrian Modelling to the Next Level for Station Design in South Africa*. South African Institute of Civil Engineering Magazine, November 2009 edition.

- Hermant, L.F.L. and Herrmann, R. (2011). *Bridge City Railway Station Project, ensuring optimum levels-of-service through pedestrian simulation incorporating Virtual Reality (VR)*. South African Institute of Civil Engineering Magazine, September 2011 edition.

Academic Presentations:

- *Microscopic Simulation Models: Pedestrian Flow Modelling*. Guest lecture presented at the University of Cape Town as part of the Transport Modelling (END 5048Z) post-graduate civil engineering course, 30 July 2010.

- *Human Movement Behaviour and Assessment of Pedestrian Space Requirements within Railway Stations: Implications for Design*. Presented at the ninth annual *Faranani* of the Southern Transportation Centre of Development (STCD), held at the Bellville Campus of the Cape Peninsula University of Technology (CPUT), 14 October 2010.

- *Pedestrian Spatial Parameters in Railway Station Environments*. Presented at the tenth annual *Faranani* of the Southern Transportation Centre of Development (STCD), held at the Civil Engineering Faculty of the University of Stellenbosch, 14 November 2011.

- *Avoiding Pedestrian Traffic Jams*. Popular presentation of PhD dissertation at the first annual STIAS PhD Science Communication Colloquium, held at the Wallenberg Research Institute of the University of Stellenbosch, 2 December 2011.

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ABBREVIATIONS

Abbreviation	Definition	Introduced in Section
2D	Two-dimensional	3.3.1
3D	Three-dimensional	3.3.1
AASHTO	American Association of State Highway and Transport Officials	2.3.7
AFV	Average Flow Value	2.1.2
AHL	Athlone, Heideveld and Langa stations	5.1.1
AM	Morning	2.1.4
ANOVA	Analysis of Multiple Variables	2.4.5
APAO	Average Pedestrian Area Occupancy	2.1.2
AR	Autoregression	6.2.3
ARIMA	Autoregressive Integrated Moving Average	6.2.3
ARMA	Autoregressive Moving Average	6.3.4
Ave.	Average	4.4.7
avi	Audi video interleave	3.3.2
BART	Bay Area Rapid Transit	2.6.2
B&A	Boarding and Alighting	1.6
BC	Benefit Cost	2.2.2
BPR	Bureau of Public Roads	2.3.3
BSI	British Standards Institute	Appendix D
CA	Cellular Automata	2.2.2
CBD	Central Business District	2.3.3
cf.	Confer (Also see Glossary)	2.3.3
CIBSE	Chartered Institute of Building Services Engineers	2.3.7
CMC	Cape Metropolitan Council	4.5.2
COCT	City of Cape Town	3.2.2
CROW	National Information and Technology Centre for Transport and Infrastructure (Dutch)	2.3.7
CTS	Calgary Transit System	2.6.2
DMP	Density measurement problem	2.2.6

Abbreviation	Definition	Introduced in Section
DNC	Data not considered	Appendix E
DOT	Department of Transport (South African)	1.3
DV	Digital Video	3.1.7
ETS	Edmonton Transit System	2.6.2
FHWA	Federal Highway Association	2.3.7
FIFA	Fédération Internationale de Football Association	6.4.1
fps	Frames per second	3.1.7
Gb	Gigabyte	Appendix E
GPS	Global Positioning System	3.1.5
HCM	Highway Capacity Manual (2000 version)	2.2.4
HMRI	Her Majesty's Railway Inspectorate	2.1.1
HMSO	Her Majesty's Stationery Office	Appendix D
Horz.	Horizontal	2.3.8
HSAG	High speed access gate (turnstile)	Appendix D
IC	Infrastructure Component	5.2.5
ID	Identity (number)	3.3.2
IEEE	Institute of Electrical and Electronics Engineers	Appendix E
IMO	International Maritime Organisation	Appendix D
ITE	Institute of Transportation Engineers	2.3.7
KCR	Kowloon-Canton Railway	Appendix D
LOS	Level-of-service	1.1
LUL	London Underground Limited	2.1.1
m	Mean (average) value	4.4.7
MA	Measurement Area	3.2.4
MA	Moving Average	6.2.3
Max	Maximum	4.4.2
MBTA	Massachusetts Bay Transportation Authority	2.6.2
MF	Magnetic Force	2.2.2
MFD	Macroscopic Fundamental Diagram	2.3.2

Abbreviation	**Definition**	**Introduced in Section**
min	minute	2.1.1
Min	Minimum	4.4.2
MRT	Mass Rapid Transit	Appendix D
ms	millisecond	3.3.3
MTR	Mass Transit Railway	Appendix D
MTS	Metropolitan Transit System	2.6.2
NFPA	National Fire Protection Association	2.1.1
NGS	Norms, Guidelines and Standards (SARCC 1997)	2.1.2
NTXY	Tracking database incorporating sample no, time and x and y co-ordinates	3.2.3
NYC	New York City	2.3.3
NYC DCP	New York City; Department of City Planning	2.3.3
NYCTA	New York City Transit Authority	2.6.3
OA	Observation Angle	3.2.5
OD	Origin-destination	5.1.3
PAL	Phase Alternating Line	3.1.7
PAR	Passenger Arrival Rate (also see Glossary)	3.1.1
PATH	Port Authority Trans-Hudson	2.6.2
Pax	Passenger/s (used interchangeably with “*pedestrian/s*” at stations)	1.2
PM	Afternoon	3.1.6
PRASA	Passenger Rail Agency of South Africa	1.1
PT	Public Transport	1.3
QOS	Quality-of-service	2.5
RCA	Radio Corporation of America	3.1.7
RPA	Railway Procurement Agency	2.1.1
SA	South Africa	3.1.4
SABS	South African Bureau of Standards	1.2
SARCC	South African Railway Commuter Corporation	1.1
SARTSM	South African Road Traffic Signs Manual	2.3.7
SCICON	School of Science and Conservation	2.3.5

Abbreviation	**Definition**	**Introduced in Section**
SD	Standard Deviation	2.3.5
SFPE	Society of Fire Protection Engineers	2.3.6
SMS	Space Mean Speed	3.2.6
SNP	Special Needs Passengers (also see Glossary)	3.1.3
SP	Spatial Parameter (usually referencing the SP-model)	1.1
SPSS	Statistical Package for Social Sciences	6.2.3
SSC	Steady State Capacity	2.3.3
STCD	Southern Transport Centre of Development	Biography
ST	Space-Time	2.5.2
STV	Space-Time-Volume	5.2.5
TCQSM	Transit Capacity and Quality of Service Manual (TRB 1999)	2.1.2
TfL	Transport for London	2.5.2
TM	Trademark	3.2.3
TMS	Time Mean Speed	3.3.3
TPF	Travel Pattern Factor (ie. either uni- or bi-directional travel)	2.5.2
TRB	Transportation Research Board	2.1.2
TTC	Toronto Transit Commission	2.6.2
TVP	Ticket Verification Point (turnstiles or other access gates)	5.1.2
UI	User Interface	5.1.3
UK	United Kingdom	2.3.7
UTS	Unobstructed Ticket System	Appendix D
v/c	Volume over capacity ratio	2.2.2
VISSIM	Verkehr in Städten - Simulations modell (Microscopic modelling software)	1.2
WCTR	World Conference on Transport Research	
wmv	Windows media video	Appendix E
XML	Extensible Markup Language	5.2.4
Xvid	video codec library following the MPEG-4 standard	3.3.1

NOTATIONS

Symbol	Unit	Description	Introduced in Section
Δ	-	Difference (between values or readings)	7.1
α	-	Level of significance	2.3.6
α_a , β_a	-	Rate of alighting or boarding passenger movement	5.3.1
α_b, β_b	-	Initial lost time prior to alighting or boarding movements	5.3.1
μ	-	Mean value	4.4.2
A	m^2	Measurement Area (MA) area	3.3.3
A, B, C, D	m	Real-world co-ordinates of the measurement area (MA)	3.3.4
A', B', C', D'	m	Image co-ordinates of the measurement area (MA)	3.3.4
A_c	pax	Alighting passengers at coach door	5.2.4
A_E	sec	Alighting end (clock time)	4.5
$a_n, b_n \ldots o_n$	pax	Passenger volumes per coach *n* according to walking speeds *a*, *b*,…o.	5.2.5
A_{pax}	pax	Alighting passenger volume	4.5.3
A_S	sec	Alighting start (clock time)	4.5
A_s	pax	Alighting passengers arriving at the base of the stairs	5.2.4
AT	sec	Alighting Time	4.5.3
B_c	pax	Boarding passengers at the coach door	5.2.4
B_E	sec	Boarding end (clock time)	4.5
B_{pax}	pax	Boarding passenger volume	4.5.3
B_S	sec	Boarding start (clock time)	4.5
B_s	pax	Boarding passengers arriving at the base of the stairs	5.2.4
BT	sec	Boarding Time	4.5.3
c	pax	Capacity	2.2.2
D_{PA}	sec	Duration of Pedestrian Activity (during the B&A process)	4.5
d_i	m	Walking distance of pedestrian *i*	3.3.3
d_i^{n-k}	m	Walking distance of pedestrian *i* between video frames *n* and *k*	3.3.3
D_t	sec	Dwell time	4.5
D_u	%	Dwell Utility	4.5

Symbol	Unit	Description	Introduced in Section
f	No.	Video frame number	3.3.3
$f_i^{\,n}$	No.	n th frame of i th pedestrian	3.3.3
$f_i^{\,in}$	No.	Frame no when i th pedestrian enters the MA.	3.3.3
$f_i^{\,out}$	No.	Frame no when i th pedestrian exits the MA.	3.3.3
F_r	-	Flow rate adjustment factor	5.3.8
FRED	m	Flow rate evaluation distance	5.2.6
k	pax/m^2	Density	2.3.2
k_c	pax/m^2	Critical density at maximum flow rate capacity (q_c)	2.3.2
$\bar{k}_i$	pax/m^2	Average density of pedestrian i	3.3.3
k_j	pax/m^2	Jam density at zero flow rate	2.3.2
L	m	Length of measurement area (MA)	3.3.3
$l_n, m_n \ldots z_n$	pax	Passenger volumes	5.2.5
M	m^2/pax	Space-density, Space module or area module. $M = 1/k$.	2.5.2
MAL	m	Measurement area length	3.2.5
MAL'	m	Measurement area length error	3.2.5
n	pax	Sample size	1.5
n	-	No. of intervals in the time period $t_i^{\,in}$ to $t_i^{\,out}$.	3.3.3
n_{60}	-	No. of times per minute that a density parameter is measured	3.2.4
N	pax	No. of observed pedestrians	3.3.3
P	pax	No. of people involved in an activity	2.5.2
P_b	%	Proportion of total boarding passengers	4.3.7
q	pax/m/s	Flow rate. $q = u/k$	2.3.2
q_c	pax/m/s	Flow rate capacity	2.3.2
R	-	ratio of boarding to alighting passenger volumes	2.6.3
R^2	-	Coefficient of determination	2.3.8
r	-	Flow ratio	2.3.7
r_g	-	Flow ratio grouping	4.4.6
ST	sec	Space-time	2.5.2
t	sec	Clock time	2.1.4

Symbol	Unit	Description	Introduced in Section
$\dot{t}$	sec	Average travel time	3.3.3
t_i^{in}	sec	Frame time of *i* th pedestrian entering Measurement Area (MA)	3.3.3
t_i^{out}	sec	Frame time of *i* th pedestrian exiting Measurement Area (MA)	3.3.3
T	sec	Time required for an activity / Observation period	2.5.2
Ta_n, Tb_n…To_n	sec	Coach alighting clock times per coach *n* per walking speeds *a*, *b*, *…o.*	5.2.5
T_d	min	Passenger arrival time before train departure	4.3.7
T_E	sec	Time end (in relation to the end of boarding activity)	4.5
T_i	sec	Time for a pedestrian to traverse the Measurement Area (MA)	3.3.3
T_S	sec	Time start (in relation to the start of alighting activity)	4.5
u	m/s	Walking speed (m/s)	2.3.2
u_c	m/s	Capacity walking speed	2.3.2
$\bar{u}_f$	m/s	Average free-flow walking speed	2.3.7
u_f	m/s	Free-flow walking speed	2.3.2
u_h	m/s	Horizontal walking speed	2.3.8
$\bar{u}$	m/s	Average Walking Speed (Space-mean-speed)	3.3.3
$\bar{u}_f$	m/s	Average female walking speed	4.3.4
$\bar{u}_h$	m/s	Average horizontal walking speed	4.4.2
$\bar{u}_i$	m/s	Average walking speed of pedestrian *i*	3.3.3
$\bar{u}_m$	m/s	Average male walking speed	4.3.4
u_i	m/s	Instantaneous walking speed of pedestrian *i*	3.3.3
$\tilde{v}$	m/s	Average Walking Speed (Time-mean-speed)	3.3.3
v or V	pax	Volume	2.2.2
w	m	Width of Measurement Area (MA)	3.3.3
$W_{n:p-s}$	sec	Walking time from coach *n* door exit (from platform) to base of stairs	5.2.5
x_i	m	x co-ordinate of tracked pedestrian *i*	3.3.4
y_i	m	y co-ordinate of tracked pedestrian *i*	3.3.4

GLOSSARY

No.	Term	Definition	Introduced in Section
1	**Apartheid**	Meaning separateness in Afrikaans (which is similar to the English "*apart*" and "*hood*") was a system of legal racial segregation enforced by the National Party government in South Africa between 1948 and early 1994.	Declaration
2	**ARIMA**	ARIMA is a generalization of an autoregressive moving average (ARMA) model. These models are fitted to time series data either to better understand the data or to predict future points in the series (i.e. forecasting).	6.2.3
3	**Auto regression**	is a model used to capture the evolution and the interdependencies between multiple time series data.	6.2.3
4	***B/A* Ratio**	The *B*/*A* ratio (*R*) is the ratio of the volume of boarding (*B*) passengers over the volume of alighting (*A*) passengers.	2.6.3
5	**Calibration**	is the establishment of default model parameter values based on literature and experiments.	1.1
6	**Capacity**	The maximum flow rate achievable through an infrastructure bottleneck. There is generally no single value of capacity, but capacity is a stochastic variant following a distribution function. (Source: Minderhoud, Botma & Bovy 1997)	1.4
7	**Capacity density**	Density at maximum flow rate capacity (q_c). Same definition as "*critical density*"	2.3.2
8	**Codec**	A codec is a device or computer program capable of encoding and/or decoding a digital data stream or signal.	3.2.3
9	**Concourse**	A concourse is a level pedestrian circulation area which links several walkways and queuing areas and may be elevated, subterranean or at ground level. (Source: Ross 2000)	1.1
10	**Confer (cf.)**	In Latin, the word *confer*, means "*compare*" or "*consult*", and is hence used to refer to other material or ideas which may provide contrasting information or arguments. The abbreviation "*cf.*" should only be used to imply a contrast or disagreement of reported facts.	2.3.3
11	**Conjoint analysis**	Conjoint analysis is a powerful way of capturing how users really value a service or product. It has been used in literature to understand how pedestrians value the features of services determining their trade-offs between different levels. (Source: Muraleetharan & Hagiwara 2006)	2.5.4

No.	Term	Definition	Introduced in Section
12	**Courtesy exit**	The term is used to define standing passengers at the doorway of a heavily laden train who need to alight in order to make way for other passengers inside the coach to disembark. Such a passenger would normally board again once the major flow has alighted.	3.2.6
13	**Critical density**	Density at flow rate capacity.	2.3.2
14	**Critical speed**	Speed at flow rate capacity.	2.3.6
15	**Crowdedness**	A performance indicator based on the levels-of-service defined by Fruin but complemented with the dimensions of time and frequency. It is a measure of QOS. (Source: Hoogendoorn *et al.* 2007)	2.2.6
16	**Dwell time**	The average time in seconds that a train is stopped alongside a platform, normally to allow passenger boarding and alighting activities to take place. (Source: TRB 1999b)	2.6.2
17	**Dwell utility**	The proportion of dwell time productively used for passenger movements, expressed as a percentage.	4.5
19	**Euclidean distance**	Straight-line distance between two points. (Source: Colclough & Owens 2009)	3.3.3
20	**Exogenous**	Refers to an action or object coming from outside a system. It is the opposite of endogenous, something generated from within the system.	2.3.3
21	**Failure period**	The peak 15-min period for evaluation of a station evacuation requirements. (Source: NFPA 130 2003)	5.2.7
22	**First-order**	Refers to "*first-order*" designs. First-order designs are two-dimensional architectural designs that is a step more detailed than conceptual sketches and typically has dimensions. Once approved, first-order designs are taken to the next level of the detail design process.	1.1
23	**Flow ratio (*r*)**	The flow ratio (r) is the percentage of one-way pedestrian flow out of the total two-way pedestrian flow. The one-way flow is the number of pedestrians passing through a pre-determined measurement section of a walking facility per meter width per minute in one direction. The minor flow is defined when $r < 0.5$ and the major flow is defined when $r > 0.5$.	2.3.3
24	**Free speed**	The walking speed of an individual when not in a crowd or in an unrestrictive environment. Free-speed typically occurs under LOS A or LOS B density conditions.	2.3.1

No.	Term	Definition	Introduced in Section
25	**Hard coding**	Refers to programming code that solves a problem, but offers no flexibility. Hard coding could be thought of as "*brute force*" programming to get the job done and it is common in every program. The degree to which a program is hard coded determines how difficult it is to change with each new type of data that is introduced or each new function that is added.	5.2.2
26	**Hawthorne effect**	an increase in worker productivity produced by the psychological stimulus of being singled out, observed and made to feel important. Also commonly referred to as the "*observer effect*".	3.1.2
27	**Heuristic**	Heuristics are "*rules of thumb*", educated guesses, intuitive judgements or simply common sense. In more precise terms, heuristics stand for strategies using readily accessible, though loosely applicable, information to control problem solving in human beings and machines.	1.1
28	**Histogram mapping**	Histogram mapping is a means to map average walking speed histograms of different infrastructure types to each other.	5.2.6
29	**Hofstede's dimensions**	Hofstede is known for his work on the four dimensions of cultural variability, commonly referred to as "*Hofstedes dimensions*". These include uncertainty, avoidance, power distance, masculinity-femininity, individualism-collectivism and Confucian dynamism. (Source: Hofstede 1991)	2.4.1
30	**Hoogendoorn rule**	The measurement standard for microscopic pedestrian assessment which follows the rule: $n_{60} \bullet A_{eff} \geq 10$ where n_{60} is the no. of measurement intervals per 60 seconds and A_{eff} is the measurement area in m^2.	3.2.4
31	**LOS-mismatch**	The phenomena where, for a particular pedestrian observation interval, discrepancies in LOS results occur depending on the criterion used, viz. either flow, speed or density.	4.4.1
32	**Macro**	A sequence of instructions written in Visual Basic (computer software language) to operate in a Microsoft Excel environment.	3.3.3
33	**Macroscopic**	The methodological term used to calculate parameters based on an aggregate volume over a certain time interval.	1.2
34	**Marker**	An attribute associated with a pedestrian that is excluded from the dataset record. Markers are typically persons who loiter within the measurement area or stand/sit or conduct activities	3.3.2

No.	Term	Definition	Introduced in Section
		that cannot be linked to walking behaviour. Marker pedestrian counts is however taken into account for the density calculation.	
35	**Mesoscopic**	Mesoscopic models fill the gap between the aggregate level approach of macroscopic models and the individual interactions of the microscopic models. Mesoscopic models normally describe the assessment entities (viz. pedestrians) at a high level of detail, but their behaviour and interactions are described at a lower level of detail.	1.1
36	**Micro-peaking**	Micro-peaking is the passenger volume peaking effects which occurs when flow rates are taken over shorter time intervals when compared to aggregate passenger volumes taken over longer intervals.	1.2
37	**Microscopic**	The methodological term used to calculate parameters based on the dynamic behaviour of individual pedestrians rather than as an aggregate volume.	1.1
38	**Moving average**	A moving average is commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. Given a series of numbers and a fixed subset size, the moving average can be obtained by first taking the average of the first subset. The fixed subset size is then shifted forward, creating a new subset of numbers, which is averaged. This process is repeated over the entire data series. The plot line connecting all the (fixed) averages is the moving average.	6.2.3
39	**Occlusion**	is a phenomena wherein two or more objects may move too close to each other and is detected as only one object. (Source: Teknomo 2002)	
40	**Occupant load**	The occupant load of a station is based on the train load of trains simultaneously entering the station on all tracks in the normal traffic direction during the peak 15- minute failure period plus the simultaneous boarding load awaiting the train. Not more than one train should unload at any one track to a platform in an emergency. (Source: NFPA 130 2003)	5.2.7
41	**Passenger Arrival Rate**	The Passenger Arrival Rate (*PAR*) is the passenger arrival flow rate distribution prior to a train arrival.	3.1.1
42	**Quantitative**	A quantitative attribute is one that exists in a range of magnitudes, and can therefore be measured. Measurements of any particular quantitative property are expressed as a	1.1

No.	Term	Definition	Introduced in Section
		specific quantity, referred to as a unit. Examples of physical quantities are distance, mass, and time. Many attributes in the social sciences, including abilities and personality traits, are also studied as quantitative properties and principles.	
43	**Qualitative**	Qualitative data are described in terms of quality (that is, "*informal*" or relative characteristics such as warmth and flavour). This is the converse of quantitative, which more precisely describes data in terms of quantity and often using numerical figures. Qualitative data describes properties or characteristics that are used to identify things. Qualitative data are generally (but not always) of less value to scientific research than quantitative data, due to their subjective and intangible nature.	2.3.8
44	**Run-off area**	Run-off areas are provided at stations to allow passengers to walk clear of critical areas such as ticket counters, lifts, stairs etc. without having to stop or change direction. Provision of run-off areas reduce the risk of circulation being impeded due to passengers stopping to orient themselves or take decisions immediately beyond. (Source: Ross 2000)	2.1.1
45	**Self-organising**	The ability of pedestrians within a complex system to interact and maintain a certain level of structure, even though each unit moves autonomously and according to strictly local information. (Source: Garrett *et al.* 2006)	1.2
46	**Self-regulating**	The "*self-regulating*" phenomena was observed by Brocklehurst (2005c) at racecourse venues where he observed that despite crowded conditions, people tried to maintain their preferred inter-personal distances between each other.	6.3.3
47	**Skywalk**	The elevated walkway (or bridge) providing access to the elevated concourse from street level.	1.1
48	**Special needs passengers**	Defined to consist of the following persons: Children between 5 and 14 years old, physically and mentally disabled, person/s laden with shopping bags, pregnant women (> 2 months), deaf and visually impaired, elderly person/s 65 years and older. (Source : Stanbury and Scott 2005)	3.1.3
49	**Steady-state**	A uniform pedestrian arrival rate.	2.3.3
50	**Streaming**	Refer to "*Self-organising*" and "*Zipping effect*" in this glossary.	1.2
51	**Stochastic**	Varied speed values (of pedestrians).	1.2

No.	Term	Definition	Introduced in Section
52	**Tarrying**	Motion of a pedestrian not going anywhere specific, i.e. with no specific or immediate destination.	3.3.2
53	**Time stamp**	The process of associating a particular time with an event.	3.2.6
54	**Validation**	Comparison of simulation data to real observations.	1.1
55	**Zipping effect**	The orderly organization of persons through a narrow walkway or bottleneck such that optimum use of space is achieved by organizing person spatial position in a zip-like fashion.	1.6

Note that reference to the Glossary (No.) is made through numerical superscripts of the first occurrence of the term in the text.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background Information

The general quality of stations and associated levels-of-service (LOS) is deteriorating in South Africa (SARCC 2005; SARCC 2006a; Britz 2011). Intersite Property Management Services, together with the Passenger Rail Agency of South Africa (PRASA), formerly the South African Rail Commuter Corporation (SARCC), embarked in 2007 on a countrywide programme to improve and upgrade commuter rail stations in South Africa. The initiative formed part of a larger upgrade process towards improving the commuter rail service in the country and achieving its vision of "*making rail the preferred mode of public transport*" (SARCC 2006a; PRASA 2009).

In 2007, the author recognized the need to develop a simple pedestrian model for aiding the planning, design and checking of pedestrian facilities at railway stations using local pedestrian behaviour rather than adopting western pedestrian behaviour and design standards. Incorporating local pedestrian behaviour as input to the design process is endorsed by several researchers including Oeding (1963); Older (1968); Navin and Wheeler (1969); Fruin (1971a); Pushkarev and Zupan (1975a); Morrall, Ratnayake and Seneviratne (1991); Seneviratne and Morrall (1985a); Tanaboriboon and Guyano (1991) who all report that different speed/flow relationships are applicable for different types of cultural populations and pedestrian facilities.

The traditional way of designing railway stations has, to a large extent, been based on heuristic[27] rules-of-thumb. Because of limited funding and the dwindling and competing space for providing such public infrastructure, the efficiency and soundness of designing such facilities deserves to and is attracting more emphasis in recent years. Accurate planning and design of pedestrian spaces for these facilities however require extensive quantitative[42] information to predict the expected performance and typically require complicated, expensive and time intensive microscopic[37] pedestrian modelling to get acceptable results. Due to the specialised data required for microscopic simulation models, calibration[5] of the pedestrian attributes and validation[54] of the model outputs is hardly ever undertaken and the default parameters packaged with commercial models is usually accepted (Axhausen and Pendyala 2001; Teknomo, Takeyama and Inamura 2000a).

It is the opinion of the author and it is hypothesised in this study, that a simple modelling spreadsheet to assist with the quantitative design process is a pragmatic way of assessing first-order[22] pedestrian space requirements for railway station designs in South Africa, where consulting funds and specialist modelling expertise comes at a premium. Towards the development of such a prototype pedestrian spatial model calibrated for South African conditions, local pedestrian behaviour and characteristics for various pedestrian facilities within the railway station environment needs to be investigated. Further study on local pedestrian characteristics is necessary to develop the fundamental speed, flow and density relationships unique to this type of application and demography.

Towards the calibration of the model, data was collected at three different types of pedestrian walking facilities, namely stairways, skywalks[47] and platforms at Bonteheuwel and Maitland railway stations located in Cape Town, South Africa. The collected empirical data formed the basis for calibrating the prototype Spatial Parameters (SP)-model developed as part of this study. It is hypothesised that the model can be used to assess the performance of pedestrian facilities at concourse[9] railway stations in South Africa.

This study is therefore about the development of an academic spreadsheet model specifically developed for the assessment of pedestrian spatial design at railway station facilities. The aim of the model is thus to support the assessment of a design with respect to its efficiency, its safety, and the quality of the pedestrian movement dynamic taking place in the design area. The design of a railway station without any form of pedestrian analysis might lead to a very costly trial and error process, which with a good analysis tool, can be effectively done at the first-order analysis level.

The primary research, conducted to calibrate the model, not only pays attention to walking on level surfaces, but covers multiple aspects of pedestrian behaviour, such as behaviour on stairs and platforms as well as boarding and alighting behaviour from rail coach vehicles.

It is not the intention of this research work to develop a fully-fledged commercial model for widespread application, but to demonstrate that a simple (mesoscopic[35] based) spreadsheet model can provide results comparative to microscopic modelling results. Though the SP-model does not replace the microscopic modelling design process, it nevertheless enables designers to use the output to produce or assess first-order designs (for further microscopic assessment) and/or for decision makers to undertake rudimentary design checks on either first-order or final designs.

1.2 Problem Statement

In South Africa, the standard procedure for determining space requirements for pedestrian areas in station building facilities uses basic macroscopic[33] principles. Experience gained by the author in reviewing design reports has shown that practitioners modify these methods slightly, according to their judgement. The net result is the same, i.e. an overall amount of space is allocated to an activity deemed sufficient to accommodate the pedestrian demand over an average time period, usually taken over 30 minutes. Demand peaking (or "*micro-peaking*"[36]), evident when assessing passenger flows for smaller time intervals and the impact of bi-directional flow and self-organising[45] or streaming[50], are not considered in the analysis at all.

Whilst working on these design review projects, it also became clear that architects were not using any quantified circulation assessments and solely employing experience, general architectural standards and referencing minimum regulatory standards such as the National Building Regulations published by the South African Bureau of Standards (SABS 1990) and an outdated Metro Station Acquisition: Norms, Guidelines and Standards document (SARCC 1997). Other South African literature sources available predominantly focus on facilities for bus and minibus termini, with no specific reference to railway station design. Work carried out by Still (2000) provided evidence that crowd behaviour "*cannot be dealt with by only using contemporary design guidance and is complex in nature*". Research is therefore needed in developing countries such as South Africa to generate the necessary behavioural database for planning railway station infrastructure. This study identified a lack of local studies in this field and has therefore contributed to addressing this deficiency.

The general heuristic rules-of-thumb for determining peak passenger (pax[a]) loads are both inadequate and misleading for detailed design purposes. Standard macroscopic design approaches suffer from a major defect with regard to analysing congestion that stems from a failure to realistically incorporate the highly variable stochastic[51] pedestrian demand phenomenon common within mass transit railway stations (Hermant, De Gersigny and Ahuja 2010). Average flows taken over the peak hour can be used as a crude preliminary estimate of the overall requirements for pedestrian space, but focussing on averages can be erroneous, as the local extremes will limit the performance of a facility. Identifying the design one-minute peak pedestrian volume by dividing the peak 15-minute flow by 15 is a common mistake. This practice does not capture the actual pedestrian dynamic and actual one-minute peaks may be significantly higher than those calculated in this way (Hermant *et al*. 2010). This is due to boarding and alighting patterns that vary greatly since boarding volumes are normally distributed over a longer time period prior to train departure whilst alighting volumes are considered more of a "*pulse load*" and the distribution of passengers over time is purely a function of the pedestrian walking speed distribution and distance to the particular infrastructure being assessed.

To address this problem and need for detailed pedestrian spatial assessment in the local engineering market, the microscopic pedestrian VISSIM module was introduced and was the first model to assess pedestrian space requirements for railway stations in South Africa (Herrmann, Hermant and Emeran 2009; Hermant *et al.* 2010; Hermant and De Gersigny 2010). The model is however, by default, calibrated on European pedestrian attributes. The author believes that pedestrian behaviour akin to railway stations in South Africa is different to those of the developed world and this study sets out to quantitatively determine this. After an exhaustive literature review exercise, it was found that no specific research has been carried out in South Africa relating to pedestrian behaviour at railway stations. Macroscopic pedestrian flow data, critical to the model calibration process, is therefore not available and so failing reliable local data, microscopic modelling continues to be undertaken with European default pedestrian attributes in this country.

Bearing in mind the intensive data requirements in setting up microscopic models, the current problem in the industry, especially in South Africa, is that it is still perceived by both clients and practitioners to be more cost effective to use macroscopic techniques and designing for a "*one-level-up-LOS*" than the required level-of-service at critical infrastructure locations.

The problem with design using the "*one-level-up-LOS*" method, is that it can unnecessarily increase the cost of a station, particularly when sizing expensive items like elevated concourse decks. Whilst acknowledging that "*micro-peaking*" volumes (over short time periods) can exceed the average macroscopic volume (taken over a longer period), the magnitude difference in the fundamental calculation results does not always translate to a LOS jump. The author believes that accurate spreadsheet calculations can be made at the

[a] *Pax is the direct abbreviation for the term "Passengers" but is also used throughout the dissertation text to define the term "Pedestrians" within the station environment.*

preliminary design stage to provide necessary spatial input to the architects prior to further testing using microscopic modelling. As previously indicated, it is not the intention of the author (through this study) to replace microscopic pedestrian modelling, but to reduce downstream design time by improving the assessment of the preliminary design through simplistic means. The development and applicability of such a simplistic model is one of the primary objectives of this study and the following steps are taken to prove this:

- By conducting extensive pedestrian behaviour observations at local stations.
- By developing a simple prototype mesoscopic-based spreadsheet model.
- By calibrating the model with the collected empirical data.
- By validating the model results against the microscopic modelling results of real case study stations.

Another concern identified by the author, is that whilst models can be developed and the animations displayed, that there is a general lack of expertise amongst certain practitioners to interpret the results of the modelling due to the complexities involved. This complexity leads to the following quotation:

> "*There is very little standard software out there that someone who hasn't designed the model and written the software could easily use – that is the state of the art in these kinds of models and may well remain like this*"
>
> Quotation by Batty, M. in seminar presentation material by John Ward, 13 May 2005

The discussion presented thus far then leads to the thesis statement for this study, i.e.

"*That the first-order pedestrian spatial requirements of concourse railway stations in South Africa can be effectively determined using a simple calibrated mesoscopic spreadsheet model.*"

The author is a firm believer in Albert Einstein's observation that "*things are best kept as simple as possible – but no simpler than that*." The thesis statement above forms the basis of this study and provides an initial viewpoint which will be argued and tested for the remainder of this study. The final thesis proposal (included in Appendix A) was submitted on 15 May 2008 and was approved by the university senate on 22 August 2008.

1.3 Relevance and Need for the Study

The relevance of the research work presented in this study can be categorised according to theoretical and practical relevance. Theoretical relevance considers aspects such as the empirical pedestrian observations that contribute to the current pedestrian behavioural database and the application of new methods and models. Practical relevance pertains to the value this research contributes towards enabling designers of railway station facilities to test or assess their designs.

No South African pedestrian behavioural data is currently available that can assist planners and designers of Metro concourse railways stations, especially with regard to addressing the spatial requirements of pedestrians. Although useful information on numerous behavioural studies worldwide is available, it is unfortunately not considered applicable to specific local conditions and situations. Much of the literature currently available is based on European, North American and Asian operations and relevance to South African operations cannot be accepted without further investigation and verification. The following quotations have provided additional motivation to conduct empirical observations in this study:

> *"Generally, we should devote at least a comparable amount of effort and resources to repeatedly observing, documenting and studying actual pedestrian and evacuation behaviour. The overhead, plan view of individuals and crowds is an especially fascinating, valuable one for study purposes."*
>
> (Pauls 2004; PED 2003 Conference)
>
> "*Research or detailed investigation on behaviour of pedestrians has been neglected in transport management.*" (Gemzøe 2001)

There is a considerable lack of empirical data and only a limited number of studies have been performed especially with regard to single-person microscopic data like walking speed (Keßel *et al.* 2002). This statement is supported by Kaup *et al.* (2007) who also mention that the greatest need in the field of pedestrian behaviour is the need for more observational data particular to the pedestrian environment, and that the studies should explicitly define the gender, ethnicity, age and cultural differences of the population being observed. The following quotation by Morrall *et al.* (1991) ideally summarises the impact of local pedestrian behaviour on the planning process.

> "*Different geographic areas yield different walking speeds and … pedestrian planning should be based on local pedestrian characteristics rather than on pedestrian characteristics from cities with dissimilar cultures*."
>
> Morrall *et al.* 1991, referring to their research on pedestrian characteristics in Canada and Sri Lanka.

It is important to note that whilst many pedestrian studies have been conducted worldwide, it is impossible to make valid comparisons between the studies because of the many variances in data collection methodologies, type of environment and the nature and density of the prevailing pedestrian population (Willis *et al.* 2004).

The need for empirical local pedestrian data is also encouraged in South Africa at a national level. According to the Department of Transport guideline document (DOT 1994), the establishment of design criteria for public transport (PT) facilities should ideally be based on empirical studies that define the characteristics and behaviour of passengers which will provide information on the distinctive effects of such behaviour on various parts of the PT facility.

The theoretical significance of this research work is therefore the determination of uniquely South African pedestrian microscopic and macroscopic characteristics not previously conducted within a railway station environment.

A simple-to-use spreadsheet based prototype model developed in this study is considered the practical significance of this research. Together with further model development, it is intended that it will be of use to experienced planners, designers and operators as well as to those people with little experience in the field, but who nevertheless have to initiate and/or approve station design projects. It is not the intention that the SP-model replace microscopic modelling, but that the model would ultimately allow practitioners to confidently assess and/or check the spatial adequacies of their first-order station designs prior to engaging expensive microscopic pedestrian modelling.

The practical relevance of this research, through application of the SP-model, will therefore contribute to addressing the needs of individual station users based on the trade-off between LOS and infrastructure costs. In other words, it will aid in avoiding both under-provision (detrimental to pedestrian operations) and oversizing of railway station infrastructure (with obvious financial implications).

1.4 Research Goals and Objectives

The dissertation has three main strategic goals. Firstly, to gain a clear idea of the limitations of contemporary station design practice within industry applied in this country and to test whether a simple prototype spreadsheet model (viz. a Spatial Parameters model) could be developed and used to assess the dynamic pedestrian spatial requirements within railway stations. It is intended that the development of the SP-model will provide support to designers of elevated concourse railway stations to test and optimise their first-order designs. The second goal of this research is to undertake extensive empirical observations and obtain pedestrian microscopic and macroscopic behavioural data in order to calibrate the model pedestrian attributes. The third goal of this research is the functional assessment of the model through application of the model to real case study projects and to comment on the model outputs.

Towards achieving these research goals, the research addressed several objectives as follows:

Goal 1

Objective 1: *To gain a clear idea and understanding of the current local industry design processes and uses of circulation analysis within station design.*

Objective 2: *To undertake a comprehensive literature review of the base theory and relevant design processes and the identification of gaps in this knowledge.*

Goal 2

Objective 3: *To undertake experimental research on pedestrian behaviour to address these gaps and gain insight into the relation between variables and dependent or response variables describing the process*. Both the behaviour of the individual pedestrian (microscopic) and the behaviour of pedestrian flows (macroscopic) is of interest, including the relation between the macroscopic density, composition of the flow (with regard to the walking direction of the pedestrians) and mean speed.

Objective 4: *To compare the macroscopic results of the pedestrian data to other countries and cultures.*

Goal 3

Objective 5: *To develop a prototypical mesoscopic spreadsheet SP-model.*

Objective 6: *To calibrate the SP-model according to the results of the local empirical data collected at stations.*

Objective 7: *To validate the accuracy of the SP-model by comparing the longitudinal results to the microscopic (VISSIM) results through the application of case studies and conclude on the accuracy and applicability of the prototype model in practice.*

Even though there appears to be existing data and knowledge within the area of pedestrian flow, it is demonstrated in this study that the current design guidance is far from comprehensively addressed and that there is limited information on the complexity that is inherently involved with accurate circulation analysis. It is also demonstrated that data and methodologies for approaching circulation space design for station design in South Africa are significantly lacking.

Due to the lack of comprehensive design guidance and data/methodologies restricting analysts to consider circulation designs in full, there is significant justification for all of the goals and objectives identified above. Fundamentally, these objectives enable further insight and provide valuable guidance for the railway station design industry.

To present a suitable prototype model for the design of railway station facilities, it was imperative to research South African pedestrian flow characteristics. Through the study of the pedestrian dynamic at stations, the relationship between pedestrian flow, density and speed was developed, which became the crucial input necessary for calculating LOS and design capacity[6]. The collection of pedestrian flow parameters at typical station walking facilities and the development of the relationship between those parameters lays the foundation for railway station design principles and spatial design capacities in South Africa. It is also expected that the results achieved in this study could be a valuable reference for other African countries or regions with similar pedestrian characteristics.

The aim of our research is to develop a simple model with pedestrian behaviour represented mesoscopically in groups taking into account collective behavioural rules in order to model platforms, staircases and other parts of the infrastructure towards determining sufficient space for pedestrian activity.

In order to provide a means of comparison, the results of the model developed in this study is compared to the results of the VISSIM simulation programme through application of case studies (refer to Chapter 6). Note that this research however does not attempt to benchmark the appropriateness of the existing spectrum of pedestrian simulation software for use as such a comparative base in this research, with the author preferring to use VISSIM for such a comparison exercise. This is because VISSIM is a simulation package which has already been established as the most recent state-of-the art pedestrian modelling software available.

1.5 Original Contribution of Dissertation

The research conducted in this study expands on the macroscopic SP-model developed in 2009 by the author (Hermant 2009) into a more detailed mesoscopic based SP-model calibrated to local operational conditions.

From the literature review (presented in Chapter 2), it is clear that there is no pedestrian behaviour data specific to railway stations in South Africa. Whilst some local (South African) studies have been conducted at street crossings and sidewalks (Van As and Joubert 1993), this is clearly not applicable to railway station environments.

The empirical study conducted in this research has, for the first time on the African continent, provided comprehensive crowd movement characteristics incorporating density, speed and flow; and their relationships including the effect of culture and other context factors within the railway station environment.

The observation sample included the investigation of microscopic movement trajectories for 24,410 pedestrians using video-based observational techniques conducted at three infrastructure environments found in railway stations viz. platforms (n = 3,455), stairs (n = 9,520) and skywalks (n = 11,435) at Maitland and Bonteheuwel stations in Cape Town, South Africa. Observations of the boarding and alighting dynamic for 7,426 passengers was also observed at these stations. Age, gender, body size, encumbrance, group size, time of day and location were the contributory attributes observed with each dataset.

Following on from this, the research will contribute towards the development of a local pedestrian behaviour database through an empirical study including demonstrating the importance of the complexity and venue specific behaviour in circulation analysis; including the sensitivity to the population profile and cultural behaviour not seen elsewhere in the world. One of the significant contributions of this research concerns the impact of cultural and gender differences on walking behaviour.

The most significant contribution of this study is however the development of a prototype SP-model towards improving the analysis of first-order designs of concourse railway station facilities. The SP-model developed consists of mesoscopically modelled processes using levels of aggregation grouped according to train coaches. We note that similar spreadsheet models have been built (Tolujew and Alcalá 2004; Laufer 2008), but these models are primarily used as input spreadsheets for commercial microscopic applications, normally applied through interface programmes, rather than direct pedestrian spatial evaluation.

1.6 Research Limitations and Assumptions

As limitations are inherent in all types of research projects, this section describes the delineation and limitations of the research conducted in this study and is specifically included to identify exactly what the study addresses and the reasons for stated omissions.

The empirical research conducted in this study has the following limitations:

- Due to the limited time frames and budget, only two local Cape Town stations were identified for empirical data collection. The stations were nevertheless carefully selected to incorporate the cultural diversity common in South Africa. The station selection process is described in greater detail in Subsection 3.1.6.

- Depending on the experimental observation areas viz. either platforms, skywalks, staircases or boarding and alighting (B&A) data, the collection of empirical data was limited to a selected subset of pedestrian attributes (e.g. gender, luggage etc.). Refer to Appendix E for more details.

- Lifts and escalators were not considered in this study as such infrastructure is not common at South African railway stations and the latter is in fact not endorsed by the rail authority, viz. the Passenger Rail Agency of South Africa (PRASA), since it is argued that it introduces an additional and unnecessary maintenance burden.

The prototype Spatial Parameters model has been developed with the following general limitations:

- The development of the SP-model and final testing of the model has been assessed against longitudinal density and flow rate results obtained from microscopic modelling through application of real-life case studies. It was not the objective of this study to assess the applicability or accuracy of microscopic models and therefore no comparative assessment of the microscopic model results against reality was conducted in this study. To do so would necessarily require an extensive validation of the microscopic model itself against real-time results to benchmark the model, which is outside the scope of this study. The SP-model results will therefore be assessed against longitudinal microscopic modelling results only. The VISSIM microscopic software package has been used for the assessment exercise, and was calibrated with the same empirical data collected in this research, in order to discount the effects of the built-in default European attributes.

- Whilst is was indicated in the previous section that the model produced in this research builds upon an earlier all-inclusive macroscopic station assessment model developed by the author in 2009 incorporating evacuation requirements, the model produced as part of this study considers spatial assessments of certain infrastructure items only, calibrated with the specific observations undertaken. The pedestrian delay occurring at turnstiles and the impact of cross-flow activity occurring at the concourse level have not been taken into account and is subject for further research. Whilst included as a model output, the validation of the evacuation assessment is also not considered in the prototype SP-model since this requires specialised experiments and data and is therefore also subject to further research.

- There are many reasons why a spreadsheet based approach to modelling will not always yield real life results. For example, inter-pedestrian differences inherent in the pedestrian traffic stream cannot be modelled macroscopically which may be considered as a limitation. However, the sensitivity of the inter-pedestrian phenomena including zipping[55], lane formation etc. on the results will be determined during the functionality assessment process of the SP-model discussed in Chapter 6.

- Other restrictions and/or limitations inherent in the development of the SP-model, as well as further model improvements is described in more detail in Section 5.4.

1.7 Thesis Approach and Structure of Report

The thesis study approach was divided into four separate stages as follows:

- Undertake a comprehensive literature review.
- Conducting empirical observations and analysis.
- Development and calibration of the SP-model.
- Functionality assessment of the SP-model through application of case studies.

The structure of the report incorporating the various stages is illustrated in Figure 1.1 and is organized into seven chapters and described as follows: This introductory chapter presents the background, motivation and objectives behind undertaking the pedestrian empirical observations, together with the purpose and scope of the study.

In Chapter 2, a comprehensive literature overview has been compiled on station design practice worldwide, base theory and pedestrian walking behaviour. Aspects relating to empirical data, pedestrian behaviour theories, models and modelling results are also discussed. The literature overview also identifies gaps in existing knowledge and establishes the need for South African pedestrian walking behaviour data incorporating pedestrian behaviour on various infrastructure types at railway stations and pedestrian boarding and alighting behaviour from train coaches.

The review of the literature provided a solid background into the available pedestrian observation techniques, which is discussed in Chapter 3. The empirical studies took place in December 2009 to take advantage of the sunlight hours during both morning and afternoon peak periods. The first two sections of this chapter (viz. Sections 3.1 and 3.2) summarises the methodology and state-of-the-art data collection techniques employed in this research respectively.

Based on this state-of-the-art, the choice was made to perform real-time observations at railway stations using video recording techniques and to develop dedicated detection and tracking software to extract microscopic data from video images. Section 3.3 describes the data recording method, selection of the data parameters and describes the data collection problems encountered during the survey observations.

The results of the empirical observations are presented in Chapter 4. Although a number of both microscopic and macroscopic relations and phenomena may be investigated from the collected empirical data, this chapter only describes the necessary regression analyses relevant for the calibration of the SP-model, consisting of walking speed distributions and variances depending on density, fundamental diagrams (i.e. the relationship between speed, density and flow) and boarding and alighting data.

The research resulted in a calibrated spreadsheet model for determining spatial requirements of pedestrians in concourse railway stations. The development of the spreadsheet model is described in Chapter 5 and the functional assessment of the model through application to case studies is discussed in Chapter 6. The chapter demonstrates the application of the model and shows how assessment studies may be performed (using the model) to evaluate facility designs with respect to pedestrian comfort and LOS criteria.

Chapter 7 concludes the dissertation with a summary of the research results and a conclusion together with a proposed list of related future research recommendations. Chapter 8 provides all the references that have been cited in the text whilst Chapter 9 provides a bibliography of literature reviewed, but which have not specifically been cited in the text.

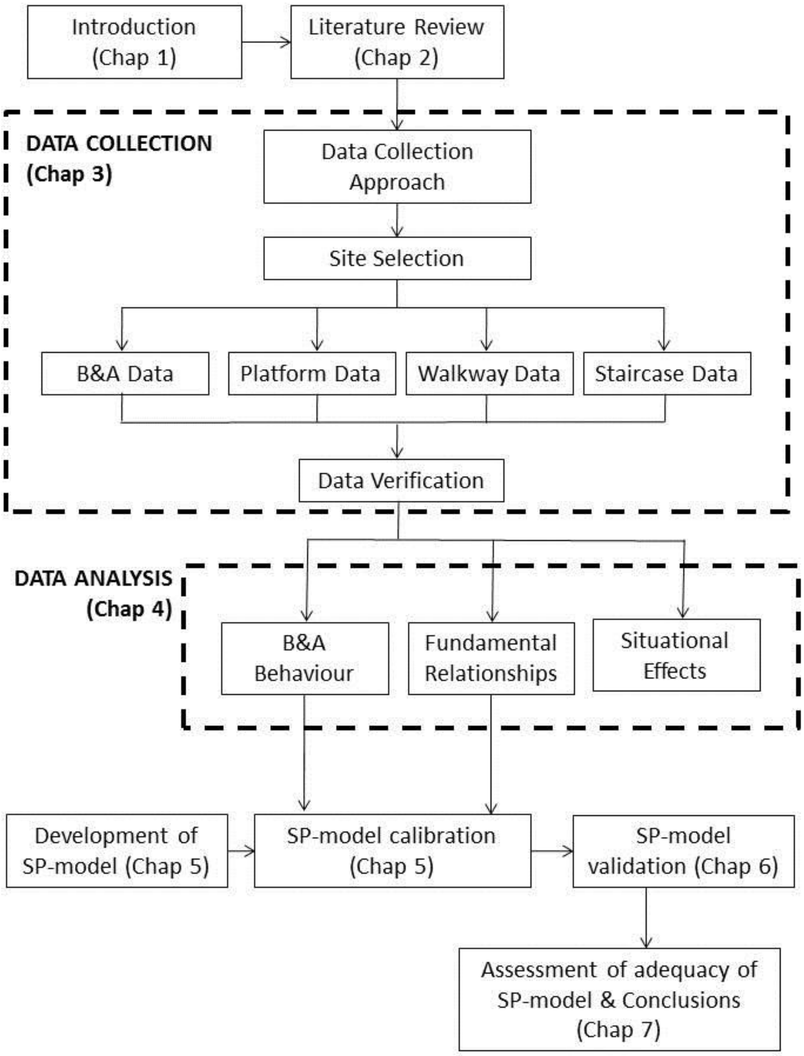


Figure 1.1: Structure of the dissertation

2. PREVIOUS RESEARCH AND CURRENT PRACTICE: PEDESTRIAN MODELLING

This chapter is an overview of existing literature aimed at both summarising the available knowledge and identifying gaps in existing local knowledge. The early portion of the literature review describes how railway station designs are addressed in various local and international guideline documents and highlights how the problem statement came about and how the research work carried out in this study addresses this.

The role of how microscopic and macroscopic models are applied to station designs is then presented which demonstrates the lack of and need for local South African empirical pedestrian data. The base theory on the fundamental flow relationships, forming the building blocks of the SP-model developed in this study is then discussed.

Previous research addressing factors which affect empirical relationships and flow behaviour in general will also be discussed. This is followed by a brief introduction to the concept of level and quality-of-service and how this is currently applied to station design.

2.1 Station Design Guidelines and Problems

In this section, various design guidelines applicable to spatial considerations within railway station infrastructure will be discussed, obtained from both international and local literature.

2.1.1 European Design Guidelines

The London Underground Limited (LUL 2005) design guidelines entitled "*Station Planning*" recommends particular levels-of-service for all infrastructure facilities (including ticket hall facilities) under normal peak conditions for the forecasted level of demand, although details are not provided what the forecast period should be. The document offers no station planning process, but rather offers generic minimum and recommended sizing requirements.

In the guideline documentation, the design of passageway, staircase and escalator widths are to be based upon average peak minute flows with the average peak minute flow defined as follows:

$$Average\ peak\ minute\ flow = \frac{peak\ 15\ minute\ flow}{15} \qquad [A]$$

The guideline document also provides factors should only three hourly or one hourly counts be available. Using the average peak one-minute flow determined from [A] however does not take into account the "*micro-peaking*" effects that may occur within the 15-minute period and facilities could be over- or under-designed as a result (Hermant *et al.* 2010). Platform widths are however based on peak one-minute platform loads (i.e. density criteria) and not on flow rate criteria.

The recommended escape capacities for the various infrastructure elements viz. stairways, passageways, escalators and turnstiles are also provided in tabular format. The guideline document also offers run-off area[44] tables (not found in any other guideline document); the run-off areas are defined as the minimum lengths between consecutive infrastructure items or changes in direction and allows for normalisation of pedestrian movement to account for pedestrian decision-making before a route choice change is necessary.

The Dutch station guideline document entitled "*Basisstation 2005, Deel A en B, Functionele normen en richtlijnen voor treinstations*" (ProRail Spoorontwikkeling 2005), provides a two-part document with Part A providing the definition of terms, station processes, station functions etc. and Part B providing more specific design norms and guidelines. The design guidelines however only offer minimum and recommended infrastructure sizes and where these are influenced by pedestrian volume, offer the design capacity. For example, for staircases, a LOS C design capacity of 38 pax/min/m[b] is indicated.

In terms of evacuation requirements, other British guideline documents such as the "*Railway Safety Principles and Guidance*" published by Her Majesty's Railway Inspectorate (HMRI 1996) and "*Generic Fire Strategy*" (Metronet 2005), the emergency requirements are similar to LUL, except that the HMRI guidelines insist that the exit route with the greatest capacity should be discounted as it could be blocked by fire. The guidelines also prescribe that it should not be possible for passengers to travel along a platform or through a train on fire.

In international building codes, such as the National Fire Protection Association (NFPA 130 of 2003), applicable to mass transit railway stations, the most basic methodology recommended for determining evacuation requirements remains the specification of a limited flow rate through passageways. In these cases, the design flow rate is the maximum, typically specified as pedestrian per metre per minute for various infrastructure elements such as platforms, stairs, doorways etc.

In summary, most contemporary design guides still recommend generalised guidelines but provide little guidance. For example, in the Irish design standards criteria viz. the Railway Procurement Agency (RPA 2006), the architectural standards for designing stairs and ramps refer to the fact that "*anticipated capacity shall be catered for*" without specific mention of allowable flow rates or LOS.

2.1.2 South African Design Guidelines

The standard procedure for determining the space required for pedestrian areas in station building facilities in South Africa is using basic macroscopic principles (Hermant, Scott and Cronje 2009b). Experience gained by the author in reviewing station design reports in South Africa has shown that design practitioners modify these methods slightly, according to their judgement with the net result that an overall amount of space is allocated to an activity sufficient to accommodate the pedestrian demand on average but which does not cater for the "*micro peaks*". Individual critical areas and smaller time intervals are not considered or analysed at all.

[b] *Readers will note that 38 pax/min/m falls within the LOS D bandwidth according to the TCQSM criteria (TRB 1999) and within the LOS E bandwidth according to the HCM 2000 criteria (TRB 2000).*

The Metro Station Acquisitions: Norms, Guidelines and Standards (NGS) document (SARCC 1997), is the current railway station design standard applicable to South Africa. In this document, the following standards as tabulated in Table 2.1 are applicable to station infrastructure design. Note that only Average Flow Values (AFV) and Average Pedestrian Area Occupancy (APAO) are provided in the guidelines and not level-of-service (LOS). Table 2.1 also provides a comparison between the associated LOS recommended in the NGS document against the LOS standards proposed by the Transit Capacity and Quality of Service Manual (TCQSM), (TRB 1999).

Table 2.1: Required LOS standards for South African station design; (Source: SARCC 1997)

NGS Infrastructure Description	TCQSM Infrastructure Description	Required AFV (from NGS)	AFV LOS (from TCQSM)	Required APAO (from NGS)	APAO LOS (from TCQSM)
Corridor	Walkway	33 – 50 pax/m/min	LOS C	0.43 – 0.71 pax/m^2	LOS C
Corridor and queuing	Queuing Area	50 – 66 pax/m/min	n/a	0.71 – 1.08 pax/m^2	LOS A/B
Walkway	Walkway	23 – 33 pax/m/min	LOS B	0.30 – 0.43 pax/m^2	LOS B
Entrance/Exit Platform queues	Walkway Queuing Area			0.83 – 1.08 pax/m^2	LOS D LOS B
Stairs (to Platform)	Stairs	32 – 43 pax/m/min	LOS D	1.08 – 1.54 pax/m^2	LOS D

From the table, the NGS guidelines offer flow rate criteria for queuing areas for which LOS cannot be determined (identified as “n/a” in the table). Although the table shows LOS matches between AFV and APAO criteria viz. columns 4 and 6, a LOS B is recommended for all walkways and queuing areas which is considered too onerous for station design. Conversely, the guidelines also stipulate that entrance/exits should be designed to LOS D requirements, which can be considered too pessimistic and is likely to be the bottleneck in emergency situations.

In terms of evacuation requirements, the NGS documentation offers no recommendations. Station design architects in South Africa however apply the SABS guideline document (SABS 1990) which stipulates that no escape route should accommodate more than 190 evacuating persons. It must however be acknowledged that these guidelines have been specifically formulated for buildings and is not applicable to mass transit facilities such as stations. Furthermore, the SABS document provides no rigid time restrictions for the evacuation requirements except that evacuation must occur in the shortest possible time.

In summary, the dimensional design of pedestrian spatial areas proposed in the NGS document involves the application of “*traffic engineering principles”* to be evaluated against the LOS guidelines proposed. It suggests that the level-of-service concept provides a useful model for the design of these pedestrian spaces and that when designing for extreme peak demands of short duration, the designer may accept a lower level-of-service standard to obtain a more economical design, but offers no guidance what this acceptable lower LOS might be or the time duration thereof. In relation to circulation guidance, exact recommendations for provisions, empirical data, and references, are not given.

2.1.3 Existing Station Design Process Problem

The NGS document (SARCC 1997) provides the following general guideline: "*all design characteristics shall be identified and the determination of the specific parameter per station shall be according to the prescribed method or any acceptable transport engineering method"* (own emphasis).

There are two problems with this general guideline. Firstly, there are no set "*prescribed methods or models/procedures*" proposed in the document. Secondly, the general guideline, "*any acceptable transport engineering method*" in the determination of station functional areas is unclear and therefore open to varied ambiguous assessment techniques making the review process and signoff particularly complicated and lengthy.

The design guidance concerns of the author is further identified in a local design report, where it was indicated that the "*NGS document is vague*" and "*there is no guidance on the spatial provisions of the concourse in the NGS and similarly, the spatial requirements for queuing at the ticket office*." (A3 Transportation Engineers 2004). Furthermore, whilst evacuation procedures are addressed separately via operating procedures from a risk management perspective, spatial provision and dimensioning for such events are not discussed in the guideline document.

The design process problem is best summarised using the words of Itami (2002) who mentioned that:

"*without a reliable method for estimating pedestrian capacities, design of new facilities becomes a "hit and miss" effort, resulting in high levels of uncertainty in determining if the time, money and resources invested in upgrading facilities will actually cater to the demand."*

2.1.4 Problems with Current Pedestrian Analysis Techniques

The general macroscopic rules-of-thumb for determining peak passenger (pax) loads are considered by the author to be inadequate and misleading for detailed design purposes. Average flows taken over the peak hour can and should only be used as crude preliminary estimates of the overall requirements for space and of cost.

As mentioned before, standard macroscopic design approaches suffer from a major defect with regard to analysing congestion. This statement stems from the failure to realistically incorporate the highly variable stochastic pedestrian demand phenomenon common within railway stations.

Focussing on averages can be erroneous as the local extremes will limit the performance of a facility. Identifying the design peak one-minute pedestrian volume by dividing the peak 15-minute flow by 15 is a common mistake and is currently still advocated in certain design guidelines (refer to Subsection 2.1.1). This practice does not capture the actual pedestrian dynamic and true one-minute peaks may be significantly higher than the average flows calculated in this way. For the purposes of this study, these one-minute peaks are termed "*micro-peaks*" or "*micro-peaking*".

Micro-peaking occurs due to boarding and alighting patterns that vary greatly and this is because boarding volumes can be distributed over a ten minute (or longer) period prior to train departure whilst alighting volumes are considered more of an immediate or "*pulse load*" and the distribution of passengers over time throughout the station infrastructure becomes purely a function of the pedestrian walking speed distribution. (Hermant and De Gersigny 2010).

To provide an indication of the effects of micro-peaking, this subsection provides some insight into the differences between the average one-minute flow rate (termed the macroscopic flow rate) and the true microscopic flow rates. Figure 2.1 shows the AM peak period volume details taken from the pedestrian modelling assessment of Langa Station (Goba 2009c).

Figure 2.1 below shows the plot of the microscopic flow rates per ten second intervals over the peak 15-minute (900 sec) AM period, from *t* = 540 sec to *t* = 1440 sec identified as the yellow block within the 30 minute analysis period. The measurement area is taken at the concourse level of the station.

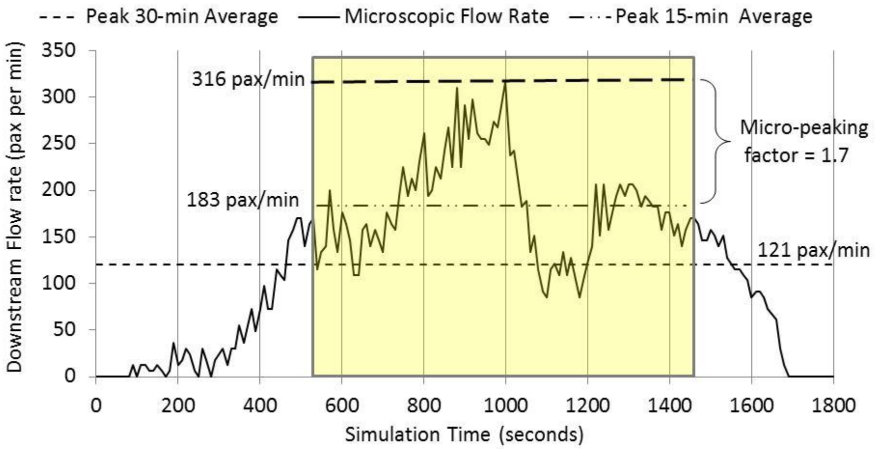


Figure 2.1: Longitudinal flow rate graph showing impact of micro-peaking; (Source: Hermant & De Gersigny 2010)

From the graph above, the peak 15-minute average macroscopic flow rate is 183 pax/min with the average 30-minute microscopic flow rate calculated at 121 pax/min. The solid line represents the simulated flow rates plotted at 10-second intervals. The actual design peak one-minute flow (i.e. 316 pax/min), occurring at around *t* = 1000 sec, in this case is 1.72 times greater than the uniform flow calculated over the peak 15-minute period. If one had to consider the average flow rate over 30 minutes, the peaking factor would be even larger with a value of 2.60. The selection of the uniform one-minute flow rate as the design volume is thus significantly lower than the true peak one-minute flow rate by up to 72%. In this case, the true one-minute flow rate exceeds the average macroscopic flow rate for approximately five minutes in duration, between *t* = 750 sec and *t* = 1050 sec.

This exercise thus highlights that average flow rates may misrepresent the micro-peaking of flows that will actually occur by a wide margin. The micro-peaking factors indicated supports the findings by De Neufville and Grillot (1982) who reported that differences in values between 50 to 100% are possible. More recent work by Laufer (2008) who conducted microscopic modelling on the North Melbourne Station revealed micro-peaking factors of 2.54 and 1.52 for platforms 1 and 3 respectively.

On the basis of these findings, it can be concluded that the average flow should not be used for the design of railway station facilities, due to the impacts of micro-peaking. The analysis shows that theoretically, a "*design peaking factor*" could be applied to the uniform flow rate to obtain the actual one-minute flow rates for any particular station. Using "*design peaking factors*" should however be used with caution as they are influenced by train scheduling and alighting volumes and is not recommended.

2.2 Pedestrian Modelling in General

The objective of including this section is to provide a brief overview of which commercial packages are readily available for modelling purposes, what types of models they are (viz. microscopic or macroscopic) and the generic advantages and disadvantages of each. Note that it is not the intention of this section to provide a detailed comparison of modelling packages.

2.2.1 Why undertake Pedestrian Modelling ?

Pedestrian models seek to replicate reality so that they can then be used as a predictive tool to inform decisions about infrastructure planning, crowd management and safety. Safety is of paramount importance when designing infrastructure and managing crowds. This is especially the case in locations where pedestrian volumes can increase rapidly, for example at transport interchanges, station platforms and sport stadium exits. Evacuation times and routes can also be tested using pedestrian modelling software.

Pedestrian modelling is frequently used for making decisions regarding the planning, design, and management of pedestrian areas. The outputs of these models can include flows on certain routes, entry and exit counts, and level-of-service (LOS) graphs. Other factors, such as costs and environmental effects, are combined with the model outputs to help make management decisions. A common use for pedestrian models is in the organisation of large, usually once-off events. These events include World Cup and Commonwealth Games, including other international sporting events such as tennis, grand prix and world championship events, and street festivals. Planning for these events is a difficult task, as there is little historical information about pedestrian behaviour and the only opportunity to collect data is at the event itself. The organisers often have several planning issues, such as the location of security barriers and food stands and whether to build or upgrade infrastructure. Modelling can assist in developing mitigation plans or decide between the infrastructure scenarios.

The topic of modelling of pedestrian streams is not new and has received attention for many years (Fruin 1971a; Navin and Wheeler 1969). In these earlier studies, the sole aim was to determine the dimension parameters of walkways. Later, the scope was extended to the field of emergency (Okazaki and Matsushita 1993; Pauls 2004). More recently, pedestrian streams are being recorded and simulated online (in real-time) at intermodal transport facilities in order to make pre-emptive infrastructure adjustments to suit the demands (Hanisch *et al.* 2003).

Pedestrian dynamics show various collective phenomena including lane formation (or "*streaming*" as defined by Klüpfel, Schreckenberg and Meyer-Köning 2003) and oscillatory flows through bottlenecks which can all be represented realistically by microscopic simulation. Microscopic modelling also shows that this self-organising flow pattern (or lane formation) can significantly change the capacity of pedestrian facilities (Helbing *et al.* 2001a).

Pedestrian models such as VISSIM simulate the progression of pedestrians through a series of geographical areas on a second-by-second basis. By calculating the flow, volume and density of pedestrians in each area, measures of congestion can be determined at each location. Planning of pedestrian facilities using conventional heuristic methods does not always guarantee the avoidance of big jams, serious obstructions and catastrophic blockages, especially in emergency situations and hence the need and advantage of microscopic modelling.

2.2.2 Introduction to Simulation Model Concepts and Types

Simulation models are becoming increasingly popular tools in assessing the performance of pedestrian infrastructure. The availability of high performance computers has resulted in an increasing interest in permitting complex microscopic simulation models. These models distinguish and track the time-space behaviour of individual pedestrians and are based on a set of rules defining pedestrian behaviour for specific situations on specific aspects (such as route choice and walking). Using these models, pedestrian behaviour and characteristics, position, speed, and walking direction of the pedestrian (referred to as agents) are recalculated for each time step. The level of detail in these various simulation models range from macroscopic via mesoscopic to microscopic analysis levels. A brief introduction to the three types of models is presented as follows:

<u>Macroscopic simulation</u>

Macroscopic models describe the agents at a high level aggregation of flow without considering its constituent parts (the agents themselves), whereas microscopic models describe the behaviour of the entities making up the traffic stream (the agents) as well as their interactions in detail. In macroscopic modelling, analogues of physical phenomena such as those describing collective agent behaviour like flows in fluids or gases are used to model pedestrian flows. Macroscopic modelling include Fruin's (1971b) level-of-service model.

In the Cell Transmission Model (Daganzo 1994), the model environment is represented by a number of small sections (cells). The simulation model keeps track of the number of agents in each cell, and every time step it calculates the number of agents that cross the boundaries between adjacent cells. This flow from one cell to the other depends on how many agents can be sent by the upstream cell and how many can be received by the downstream cell. The amount of agents that can be sent is a function of the density in the upstream cell and the number that can be received depends on the density of the receiving cell.

The use of macroscopic simulation tools has grown extensively, particularly with regard to vehicular based modelling and has been facilitated by the development of extensive traffic measurement systems that have been installed in major urban areas and motorways. According to Burghout (2005), an additional factor that has helped macroscopic models gain popularity is the fact that the data needed for such models (flow counts, speeds) is at the same level of aggregation as the data that can be supplied by the measurements.

Most of the research done to date on pedestrian dynamics and behaviour have been done at the macroscopic level (Fruin 1971; TRB 1985). Macroscopic modelling however does not consider the interaction between pedestrians and is therefore not well suited for the prediction of pedestrian flow performance in pedestrian areas or environments that include obstacles which reduce the effective movement area available.

Microscopic simulation

Microscopic simulation is modelling of pedestrian movement where every agent in the model is treated as an individual. A large number of microscopic simulation models have been developed, examples of which are VISSIM (PTV Traffic Mobility Logistics 2008), Legion (Still 2000), Nomad (Hoogendoorn and Bovy 2003), Pedflow (Willis *et al.* 2002), the social force model (Helbing and Molnár 1998), and Streets (Schelhorn *et al.* 1999). Legion is proprietary software specialising in modelling crowd behaviour and was first developed as a model of ingress and egress for major events (Still 2000). Like all microscopic models, it treats each person as a "*virtual person*" who senses their environment and makes decisions about where to move accordingly.

The microscopic suite of models is essentially based on three algorithmic platforms briefly described as follows:

A: Benefit Cost (BC) Cellular Model: This model was proposed by Gipps and Marksjö in 1985 and simulates the pedestrian agent as a particle in a cell. Each cell can be occupied by at most one agent and a score is assigned to each cell on the basis of proximity to other pedestrians (cell agents). The cell scores represent the gain that can be achieved by the agent when moving toward the destination. The score is calculated in the eight-cell neighbour of the pedestrian (including the cell location of the agent itself). The agent will then move to the next cell that has maximum net benefit. This methodology is similar to the one used in the STEPS pedestrian simulation software developed by Mott MacDonald.

A similar approach to the BC cellular model, is the cellular automata (CA) modelling technique proposed by Nagel and Schreckenberg (1992), where pedestrian agents occupy cells on a grid and move according to slightly different but simpler rules depending on the availability to move to adjacent cells. As per the BC model, these models generally use a grid-based platform where each cell size is sized to allow for occupation by one agent only; hence the representation of large areas requires a large number of cells.

The representation of the CA model environment includes two layers of information: a static layer pointing to the pedestrian destination and a dynamic layer containing the general direction of the crowd. Each pedestrian agent uses the information of their particular cell to decide which of the eight neighbouring cells to move to next.

B: Magnetic Force Model: The application of magnetic models and equations of motion using the analogy with magnetic fields as the basis for pedestrian movement was first developed by Okazaki (1979). In a magnetic force (MF) model, each pedestrian and all obstacles are assigned a positive pole. A negative pole is assumed to be located at the destination goal of the pedestrians.

Pedestrians thus move to their goals and avoid collisions through the manifestation of two types of forces working on each pedestrian. First, a magnetic force (as formulated by Coulomb's law), which is dependent on the intensity of the magnetic load of a pedestrian and the distance between the pedestrian and the destination, attracts the agent to the destination. Another repulsive force acts between pedestrians and pedestrians and obstacles to avoid the collision with other pedestrians or obstacles respectively. The total of all forces from the destination node, walls and other pedestrians that act on each pedestrian decides the direction and velocity of each pedestrian for each assessment time interval.

C: Social Force Model: The Social Force Model was developed by Helbing (Helbing 1991; Helbing 1992) together with Molnar and Vicsek, which has similar principles to both the Benefit Cost cellular model and the Magnetic Force model. Helbing used the notion of attraction and repulsion to model microscopic behaviour and developed complex equations to model a range of pedestrian behaviours, commonly referred to as the "*social force*" model (Helbing and Molnár 1998; Helbing *et al.* 2001b).

In the Social Force Model, a pedestrian is subjected to social forces that motivate each individual pedestrian. The summation of these forces act upon a pedestrian which creates movement in a particular direction. The model is based on the assumption that every pedestrian has an intention to reach a certain destination at a certain target time and the direction is a unit vector from a particular location to the destination point. The model is based on the theory of fluid flow, particle systems, and flocking (Helbing *et al.* 1997). Similar approaches have been developed by Still (2001), and Hoogendoorn, Bovy and Daamen (2004).

<u>Mesoscopic simulation</u>

A third 'class' of traffic simulation models is gaining popularity. The so-called mesoscopic models fill the gap between the aggregate level approach of macroscopic models and the individual interactions of the microscopic models. Mesoscopic models normally describe the assessment entities (viz. pedestrians) at a high level of detail, but their behaviour and interactions are described at a lower level of detail. These models can take varying forms.

One form is agents grouped into uniform packets, which are routed through a network. The group of agents acts as one entity and its speed on each infrastructure link is derived from a speed-density function defined for that link. If there is a high volume of agents on the link (i.e. the density is high), the speed-density function will give a low speed to the agents, whereas a low density will result in a higher allocated speed. More complex attributes like acceleration and deceleration of agents is not modelled.

A queue-server approach is used in some models where the walkway is modelled as a queuing and a running part. Although the agents are represented individually and maintain their individual speeds, their behaviour is not modelled in detail. The agents traverse the walkway with a speed that is determined using a macroscopic speed-density function, and at the downstream end a queue-server transfers the agents to other connecting walkways or destination nodes. This last approach combines the advantages of dynamic disaggregated flow modelling with the ease of calibration and use of macroscopic speed-density relationships. The queue-server approach is however difficult to model when demands exceed server capacities viz. when *v/c* > 1.

2.2.3 Advantages and Problems of Microscopic Modelling

While macroscopic models have the ability to simulate large networks efficiently, they generally lack the level of detail needed in modelling the individual pedestrian's route choices (due to the fact that pedestrians are not modelled individually). Modelling the effect of obstacles is therefore difficult in such model types. Microscopic models on the other hand are well suited to model responses of pedestrians to a magnitude of information sources in some detail. However, the detailed nature of their operation requires careful coding of all network details, due to the sensitivity of the results to coding errors. In addition, these models are sensitive to errors in the setting of their many parameters and need to be carefully calibrated.

Also, for the reasons mentioned above and due to the computational time of the detailed simulation of every pedestrian in the network, the size of the networks that can realistically be simulated with microscopic models is limited. Mesoscopic models fills the gap between microscopic and macroscopic models, by providing modelling of the walking behaviour of pedestrian groups instead of modelling individual behaviour. This makes mesoscopic models ideal for prediction applications, where the detailed modelling of the pedestrian interaction with the environment is essential, but where detailed route choice modelling is not needed.

Advantages:

Microscopic techniques provide insight to the behaviour of a system under a wide range of conditions provided the user does not become too ambitious with the scope of the technique. It is an excellent discovery tool and can provide valuable information over a wide range of behavioural inputs. When flow through a specific geometry is unknown, a microscopic technique should be applied as part of the analysis process. This allows operators to test sections of their environment for behavioural dynamics. As an example of this discovery process, Helbing *et al.* (2001a) observed that pedestrians flows tended to self-organise (manifested via lane formation) and observed oscillatory flows through bottlenecks. He noted that self-organisation flow patterns could significantly change the capacities of pedestrian facilities and that this phenomenon should be taken into account while designing efficient pedestrian spaces.

Problems:

According to the TCQSM (TRB 1999c), microscopic computer simulation models for pedestrian circulation is continually under development and to date have generally involved significant manual input or have been limited in their ability to represent the complex multi-directional movements of pedestrians.

According to Teknomo (2002), most of the microscopic pedestrian models have not been calibrated using microscopic level data. Teknomo concludes that these models therefore have no statistical guarantee that the parameters will work for general cases or even for a specific region. Such calibration is not possible without the ability to measure individual pedestrian movement data.

In fact, Hooogendoorn and Daamen (2006) have stated that it is still "*unclear if microscopic models are able to describe individual walking behaviour accurately, or if they mainly provide a reasonable average macroscopic prediction*".

Microscopic model building is very expensive, both in terms of time and expertise to interpret the results. A vast array of data input and output can be produced and, as analytical data is concerned, it can provide a blanket behavioural test required for a complete understanding of a system. However, one would rarely know if there was a problem in the model, a problem in the code or the behavioural output of the model if a small change in the environment were suddenly introduced. One example where these kind of models could fail completely would be the sudden change in the environment (say heavy rain for example) where the position of the "*little old lady*" will now have a considerable effect on the crowd dynamics.

A similar problem exists when microscopic models are built for complex spaces, where the user does not know which element or obstacle may hold the critical factor for the accurate prediction of the system as a whole. Various pedestrian microscopic models produce different results for the same input. This is because the models make different underlying assumptions about the dynamics of individuals. To know the limitations of a system requires intimate knowledge of a wide range of techniques that underpin the various commercially available tools.

A further problem of microscopic modelling techniques identified by Gupta (2005) is that all pedestrians are treated as identical, namely that there is no consideration given to group movement. Another issue is that individuals in microscopic models can only scan one step ahead when in reality, persons scan up to ten or more steps ahead while choosing their next step. Another shortcoming identified by Keßel *et al.* (2002) in the current modelling algorithms is that a backstep is not allowed. Also, by definition, the social force model does not allow physical contact between individuals in crowded situations.

2.2.4 Advantages and Problems of Macroscopic Modelling

Most of the pedestrian studies that have been carried out are on a macroscopic level. Macroscopic pedestrian analysis was first suggested by Fruin (1971b) via the LOS model which is still followed by many researchers and has been adopted by the *Highway Capacity Manual* (HCM), (TRB 2000).

Advantages:

Macroscopic modelling techniques form the basis of the existing, tried and tested codes of practice around the world. Macroscopic pedestrian data-collection is simple and is recommended by most guideline documents wherein all pedestrian movements in pedestrian facilities are aggregated into flow, average speed and average density. The models are quick and easy to apply and conforms with accepted data and field observations. The main application of macroscopic pedestrian studies is towards the adequate space allocation for pedestrians in pedestrian facilities. It does not consider the direct interaction between pedestrians and it is not well suited for prediction of pedestrian flow performance in pedestrian areas or buildings incorporating street furniture (kiosks, benches, telephone booths, etc.).

Problems:

There is a wide body of science associated with macroscopic modelling. For instance, fluid dynamics (a tried, tested, proven and applied discipline) uses a macroscopic model to analyze fluid behaviour, i.e. where the interaction of every particle in a fluid is not modelled but relies on the behaviour of the fluid as a large scale interactive system. Thus frictional forces, flow, and pressure/density are the macroscopic terms associated with fluid motion.

A crowd can be successfully modelled using flow, level-of-service, probability of conflict, queuing models and shockwaves. One however needs to rely on trustworthy data and an understanding of the systems behaviour over a wide range of inputs. To model a crowd using macroscopic models, one needs to state the underlying assumptions and work in the domain of statistics and probability. The tools used to create macroscopic models therefore need to be based on solid, reliable, tried and tested results.

The bulk of pedestrian planning and design, evacuation and contingency planning and architectural/building codes of practice are macroscopic models. They are applied because, by and large, they are proven to work. There is always room for improvement and the wide range of modelling tools currently available shows that the industry is applying some of the best minds to the on-going problems of crowd dynamics.

In summary, some of the advantages and disadvantages of pedestrian simulation on the microscopic and macroscopic levels were briefly presented above. In general, for microscopic modelling, the disadvantages are by and large connected with the resource requirements necessary to develop, calibrate, validate and experiment with the model. The output data precision could however be mentioned as an advantage. Macroscopic modelling, on the other hand, requires less input data for model development and typically ensures all the station design guidelines have been met. More importantly, due to imbalanced cross flows and micro-peaking effects, it could also, according to Knutton (2004), cause the failure of the original layout to occur.

2.2.5 Advantages and Problems of Mesoscopic Modelling

A Mesoscopic model fills the gap between the aggregate level approach of the macroscopic model and the individual interactions of the microscopic models. Mesoscopic models normally describe operations at a high level of detail, but their behaviour and interactions are described at a lower (aggregate) level of detail. These types of models can take on various forms where pedestrians are typically grouped into "packets", which then are considered to behave as one entity and their speed on each infrastructure link is derived from a speed-density function for that link at the moment of entry. The speed-density function relates to the speed of the pedestrians in relation to the prevailing density. A high volume of pedestrians on a link would present a low speed to the pedestrian "packet" whereas a low density will result in higher allocated walking speed.

<u>Advantages:</u>

Mesoscopic models allows for the modelling of groups of uniform individuals, but limits the level of detail in which the supply side (individual inter-personal behaviour) is simulated. The groups that are defined in the model usually represent homogenous entities that can be modified with mathematical formula in every step of the discrete simulation. This makes mesoscopic models ideal for higher-order applications, where strategic infrastructure choices are required, but where the detailed modelling of individual behaviour and environments is not needed. Due to the limited detail required for mesoscopic models, their inputs can be easily changed and expanded. According to Savrasovs (2010), the development time of a mesoscopic model is approximately five times less than the development time of the same microscopic model.

<u>Problems:</u>

It has been reported by Savrasovs (2010) that since mesoscopic modeling was specifically developed to operate between the micro and macro environment, that we can expect mesoscopic models to "*not have the disadvantages that micro and macro models have, but which have the advantages of both*". Mesoscopic models are however not particularly suited to modeling elements that do not have clearly defined homogenous entity groups. Furthermore, mesoscopic models do not operate well in over-congested environments, where behavioural patterns operate at the extremes of the speed-density functions. Queuing behaviour, leading to time delay and foreshortening of infrastructure links, can also not be well represented in a mesoscopic model.

2.2.6 Application of Modelling Results to Station Spatial Assessment

It is the intention of this subsection to provide the reader with a background of what type of and how the various longitudinal results of pedestrian models can be used to assist in the design of pedestrian infrastructure, specifically for railway stations.

The procedures for determining station infrastructure requirements applied later in the case studies viz. Chapter 6 has been based on a relative scale of pedestrian comfort and convenience. Procedures for evaluating pedestrian capacity and level-of-service (LOS) are contained in Fruin's book entitled *Pedestrian Planning and Design* (Fruin 1971a). Procedures for analysing pedestrian circulation on sidewalks, street corners and crosswalks are also presented in the *Highway Capacity Manual* (TRB 2000). More applicable

LOS standards appropriate for railway station facilities are presented in the TCQSM series of documents (TRB 1999).

Whilst the procedures mentioned above provide a static reference to standards (i.e. providing results for snapshot data), there is currently no internationally accepted standard that introduces the dimension of time to the evaluation process. This is attributable to the recent introduction of sophisticated modelling software to the engineering industry capable of providing output results in very short intervals. Towards the development of longitudinal LOS assessment standards, Hoogendoorn *et al.* (2007) proposed the following assessment criteria with specific reference to longitudinal (time-based) results for the assessment of railway station designs. They proposed that the infrastructure being evaluated would require resizing or re-design if one or more of the following criteria are met:

- If the infrastructure LOS results exceeds the acceptable LOS criteria greater than three times in the peak period, (although a time duration is not specified),
- If the total duration of infrastructure LOS results exceeds acceptable LOS for longer than five minutes per peak period,
- If the consecutive duration of unacceptable LOS results lasts for longer than 30 seconds[c], or
- If the infrastructure LOS operates at or over the acceptable LOS limit and affects at least 1000 passengers per peak period.

Note that the station LOS design guidelines outlined by Hoogendoorn *et al.* above is only considered a suggestion at this stage and is currently not stipulated in any local or international station design guideline documentation. There are currently no policies indicating what the acceptable time periods for which poor LOS can be tolerated within station facilities. This time period and the decision to review station infrastructure to conform to the LOS standard remains the prerogative of the rail authority in South Africa.

The next issue to consider is which LOS criteria should be utilised for evaluation purposes, whether it be flow rate, speed or density criteria. According to Saif (2009), LOS results vary for the three fundamental criteria and argues that the average speed criterion always results in the lowest levels of LOS, followed by density, then by flow rates. Fruin (1971a) and Hoogendoorn *et al.* (2007) however prefer that the passenger density parameter is considered as the best measure of the so-called "*crowdedness criteria*"[15] since speed and flow are usually not applied to pedestrian traffic. They argue that flows, often used as a base measure in road traffic is less suitable for pedestrian traffic, because without extra information on the prevailing speed or density, it is unknown if there is congestion or not.

A word of caution when using the density criteria however, is that the average measured density is significantly dependant on the location and size of the measurement area and the way that pedestrians distribute themselves over the measurement area is also important. Zacharias (2001) observed that pedestrians do not distribute themselves evenly across the walking space and suggested that the design and

[c] *According to a literature review by Hoogendoorn et al. (2007), passengers become impatient and more reckless when they must wait for more than 30 seconds.*

layout of such spaces should be studied to derive more realistic levels-of-service. This problem, defined here as the "*Density-Measurement Problem*", (abbreviated DMP) is shown in Figure 2.2 and explained as follows.

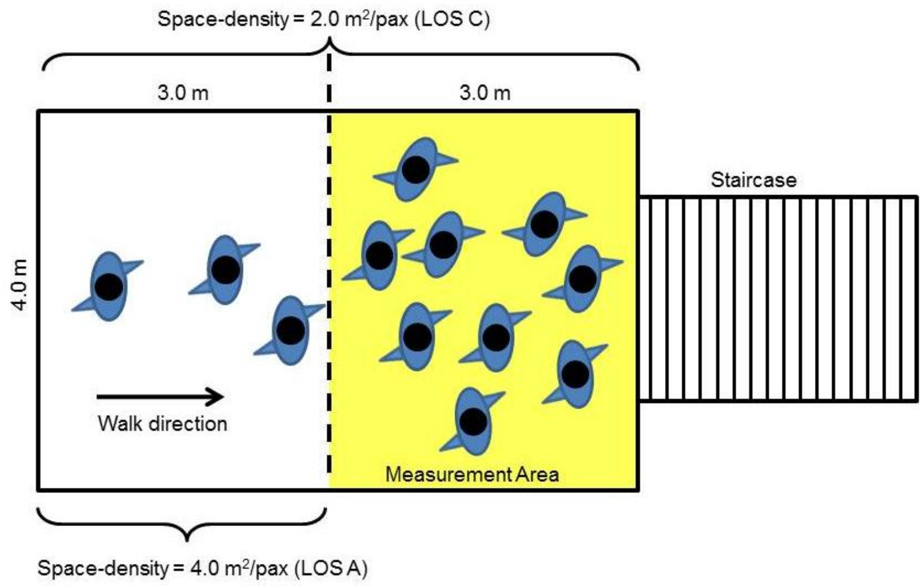


Figure 2.2: The Density-measurement problem; (Source: Hoogendoorn *et al.* 2007)

The figure shows a density for two identical areas of 12 m^2 with the yellow coloured area closest to the staircase experiencing a space-density (*M*) of 1.3 m^2/pax (LOS D) and the furthest area experiencing a space-density of only 4.0 m^2/pax (LOS A). The combination of the two areas however calculates to a space-density of 2.0 m^2/pax (LOS C). This hypothetical DMP situation reveals that three measurement areas could yield three different density LOS results. This highlights the importance of the careful selection of measurement areas.

2.3 Pedestrian Movement Dynamic

2.3.1 Introduction

Empirical study into pedestrian behaviour has been carried out over the last 50 years by various researchers. It will be shown that most of the observations on pedestrian behaviour has been based on studying empirical data gathered from site observations, photographs or videos observed at different locations and conditions.

The literature review of past research will show that there can be many influences on free speeds[24] and flow rates and this section will introduce the importance of such influences. From the work carried out, there appears to be varying capacity flow rates on both stair and level walking routes depending upon the situation. It can also be stated that there is not a comprehensive set of research data for all environments and conditions.

This section first provides the theory base behind the macroscopic fundamental relationship with respect to pedestrian traffic flows. The second part of this section gives an overview of empirical data and related research conducted worldwide. The third part deals with mean speed, flow, and density as macroscopic variables for both level and stair terrain. In the final part of this section, conditions influencing the fundamental diagrams are described, including (but not limited to) the influences of age, gender, and type of walking infrastructure.

2.3.2 The Standard Macroscopic Fundamental Relationship

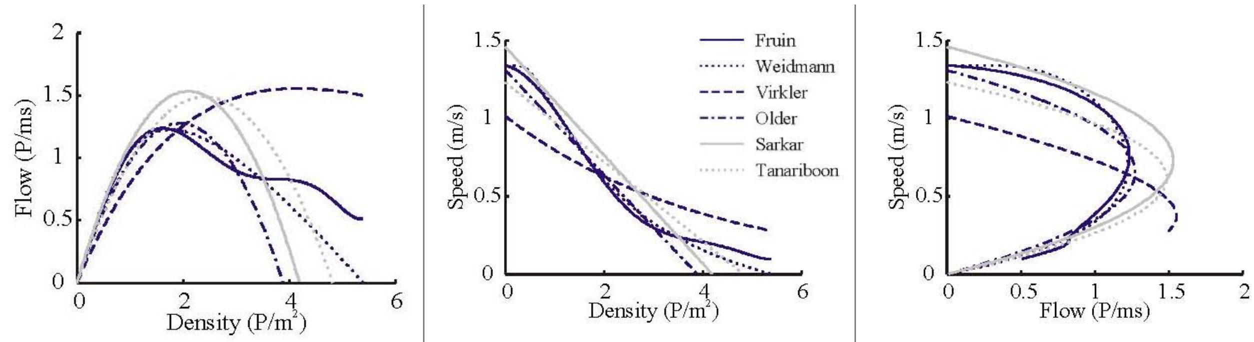
This subsection describes the empirical data, theories, models and modelling results with respect to walking behaviour. However, first an overview is given of the process of walking, followed by definitions of frequently used terms describing macroscopic walking characteristics.

Vehicle traffic flow theory reveals the fundamental relationship between vehicle flow, density and speed as follows: with the increase in density, the flow goes up gradually until the critical density[13] is reached, after which a rapid decrease in the flow at or beyond the critical density occurs. As the density increases, the speed reduces at a uniform rate until it reaches zero, when traffic stagnation occurs.

The following relation, referred to as the macroscopic fundamental relationship is valid for all types of flows:

$$q = u.k \qquad [1]$$

where q is the flow (in pax/m/s), k is the density (in pax/m^2), and u is the walking speed (in m/s). The graphical representation of the relationships between these macroscopic characteristics are defined as the "*macroscopic fundamental diagrams*" or MFD. As indicated in Figure 2.3, three MFD diagrams are possible from the relationship defined in [1], namely flow (q) vs. density (k) shown in (*a.*), speed (u) vs. density (k) shown in (*b.*) and speed (u) vs. flow (q) shown in (*c.*). These three relationships represent the same information so that from one relation, the other two may be calculated. The figure shows examples of the MFD relationships derived by Older (1968); Fruin (1971b); Tanaboriboon, Hwa and Chor (1986); Weidmann (1993); Virkler and Elayadath (1994) and Sarkar and Janardhan (1997). The reason behind the variation in the various curves will be discussed later in this section.



(a.) q vs. k *(b.) u vs. k* *(c.) u vs.q*

Figure 2.3: Macroscopic fundamental diagrams from literature; (Source: Daamen *et al*. 2005)

Both Older (1968) and Fruin (1971b) demonstrated that, for most densities, speed reduces linearly with increasing density as shown in Figure 2.3 (*b.*). As first observed by Older (1968) on city streets in London, as the density increases, the flow rate will reduce until a point where the flow rate reaches a maximum flow rate.

In order to complete the theory base for the MFD relationship, it is important to describe a few definitions and their meanings. Figure 2.4 shows a typical flow (q) vs. density (k) relationship for pedestrian traffic, where the following points on the MFD diagram need to be defined:

- Free-walking speed u_f : This is the mean speed if q = 0 pax/m/s and k = 0 pax/m^2; it equals the slope of the q vs. k function at the origin.
- Flow rate capacity q_c: This is the maximum flow rate achievable, also called critical flow. Due to the relation between density and speed, the maximum flow is not achieved at the maximum walking speed.
- Capacity density[7] or critical density k_c : This is the density when $q = q_c$.
- Capacity speed u_c : This is the mean speed when $q = q_c$.
- Jam density k_j : This is the density when u = 0 m/s, q = 0 pax/m/s and $k > k_c$.

The region of the q vs. k function in which densities are greater than the capacity density (i.e. $k > k_c$) is called the "*congestion or unstable flow region*", whereas the region with densities lower than the capacity density (i.e. $k < k_c$) is called the "*free flow or stable flow region*". Note that the maximum flow rate (q_c) often occurs at the density LOS E/F boundary and so the above terminology in the context of free-flow, by definition, is not entirely correct.

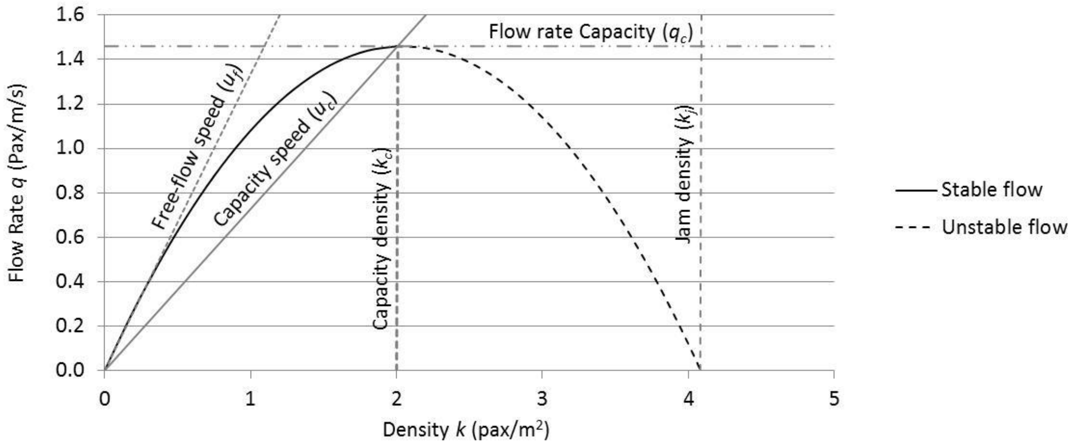


Figure 2.4: Flow (*q*) vs. density (*k*) relationship for pedestrian flow

Pedestrians can choose their preferred walking speed at low pedestrian densities, but both flow and speeds decline under crowded conditions. It is recognised within various research that free speeds occur at relatively low densities. Fruin (1987) noted the density at which this happens on level routes appears to be in the region of $k \leq 0.5$ pax/m^2 but that pedestrians are willing to accept higher densities than they normally would if this leads to a positive incentive. Muramatsu, Irie and Nagatani (1999) found that the jamming density (k_j) does not depend on the size of the area in which the congestion occurs.

2.3.3 Past Research on the Macroscopic Fundamental Relationship

This subsection provides a literature review of relevant pedestrian related studies that have been carried out worldwide including the analysis techniques used. It should however be noted that other relevant literature is referenced throughout the body of this dissertation. Some of the more important and influential research on empirical pedestrian data worthy of discussion is chronologically tabulated in Table 2.2. The table shows escalating research activity in this relatively new field since the 1960's.

Table 2.2: Chronological details of pedestrian research conducted worldwide

Researcher/s	**Year**	**Location**	**Research Details**
Oeding	1963	Germany	Studied the relationship between speed and flow for different types of pedestrians.
Older	1968	London	Examined pedestrian flow characteristics in Oxford Street, London.
Navin & Wheeler	1969	USA	Investigated pedestrian flow characteristics on walkways at three locations at the University of Missouri campus, Columbia.
Predtechenskii & Milinskii	1969	Russia	Developed the speed-density relationship on walkways and stairs under normal and emergent situations.
Fruin	1971	USA	Proposed the level-of-service (LOS) concept for pedestrian flow and developed the design criteria for pedestrian facilities.
Pushkarev & Zupan	1975	UK & USA	Compared the flow characteristics of shoppers in London with the characteristics of commuters in New York.
Polus *et al.*	1983	Israel	Studied pedestrian flow on sidewalks in Haifa and used a three-part piecewise linear fit to model the speed-density relationship.
Seneviratne & Morrall; Morall *et al.*	1985, 1991	Canada and Sri Lanka	Compared pedestrian flow characteristics between Canada and Sri Lanka in the Central Business districts (CBD's).
Tanaboriboon *et al.*	1986	Bangkok, Thailand & Singapore	Analysed pedestrian movement at three locations in Asia and revealed that Asians should not directly use the design criteria proposed by Western guidelines.
Davis & Braaksma	1988	Canada	Conducted observations at three airports in Canada on baggage-laden and un-laden pedestrians and found that baggage did not significantly impact free-flow speeds.
Ando *et al.*	1988	Japan	Presented data on the relationship between speed and density on a level surface and for the ascending and descending direction for stair movement in several railway stations.
Daly *et al.*	1991	London	Analysed the pedestrian speed-density relationship for passageways, stairs, platforms and other facilities in London underground stations and reviewed the design parameters including free-flow speed, capacity and speed at capacity for those facilities.
Al-Masaeid *et al.*	1993	Developing countries	Made some suggestions for the standard of pedestrian planning for developing countries based on research on the speed-density relationship in the CBD of several developing countries.
Lam *et al.*	1995	Hong Kong	Conducted a comprehensive study on pedestrian flow characteristics for different facilities including sidewalks, outdoor walkways and stairs. It was revealed that flow characteristics in Hong Kong, China are similar to those in Singapore.
Sarkar & Janardhan	1997	India	Carried out surveys at an intermodal transfer terminal in Calcutta and fitted curves of flow-density, flow-speed and speed-density.
Cheung & Lam	1998	Hong Kong	Observed pedestrian route choice between stairs and escalators and developed travel time functions using the Bureau of Public Roads (BPR 1964) function.
Lam & Cheung	1999	Hong Kong	Observed that pedestrian stair ascending speeds are lower than the descending speeds in Hong Kong underground stations.
Lam & Cheung	2000	Hong Kong	Calibrated the pedestrian speed-flow relationships for the main facilities in Hong

Table 2.2: Chronological details of pedestrian research conducted worldwide

Researcher/s	Year	Location	Research Details
			Kong underground stations.
Lam *et al.*	2001	Hong Kong	Observed that bi-directional flows on walkways have significant impacts on both the at-capacity speed and the maximum flow rates. They found that the more unbalanced flow ratio[23] provides lower capacity and speed.
Daamen & Hoogendoorn	2003	Netherlands	Data from controlled walking experiments conducted in the Civil Engineering Faculty building were used to develop fundamental flow diagrams for bottleneck flow situations.
Fujiyama &Tyler	2004	London	Conducted stair speed observations and observed no relationship between stair walking speed and age.
Willis *et al.*	2004	York & Edinburgh, UK	Conducted sidewalk observations of 2,613 participants for uncongested conditions. Age, gender, group size, level of mobility, time of day and location was found to have significant effect on average walking speeds.
Cepolina & Tyler	2005	London	Observed the "capacity-drop" phenomena at a bottleneck (on a level walkway to stairs interface) where a maximum capacity of +20% of the steady-state[49] capacity (SSC) and -25% of SSC at the capacity drop was observed.
Lee & Lam	2005	Hong Kong	Observed normal distributions for pedestrian speeds on both walkways and staircases.
Wang & Liu	2006	Simulation only	Found by simulation, that maximum flow rates dropped when flow ratios changed from fully uni-directional (r = 1.0) to a 50:50 directional distribution (r = 0.5).
NYC DCP	2006	New York City	Sidewalk observations of 8,871 pedestrians on NYC sidewalks confirmed that age, gender, group size, level of mobility, time of day and location was found to have significant effect on average walking speed and the fact that luggage does not affect average walking speed significantly.
Finnis & Walton	2007	New Zealand	Conducted walking observations which did not support that pedestrian walking speed is indicative of pace of life (or population size).
Ye *et al.*	2008	China	Carried out empirical surveys in Shanghai metro stations and produced pedestrian flow characteristics and fitted equations for passageways and stairways. They found that the more unbalanced flow ratio of the two-way passageway gives a higher capacity and speed at the same pedestrian density.
Daamen *et al.*	2008	Netherlands	Conducted controlled boarding and alighting experiments.
Kretz *et al.*	2008	Netherlands	Carried out 485 horizontal speed measurements on a staircase at a Dutch pavilion at the Expo 2000 in Hannover.
Saif	2009	Saudi Arabia	Carried out observations of worshippers en route to the Holy Mosque on Khalid Bin Alwaleed Road, Makkah, Saudi Arabia and developed macroscopic fundamental relationships and equations.

Much literature can be found on pedestrian walking behaviour, although, as can be seen from the table, few sources have been dedicated to public transport facilities. Significant effort has gone into developing a level-of-service concept as given in seminal research by Fruin (1971b); Mori and Tsukaguchi (1987) and Polus, Schofer and Ushpiz (1983).

Much work has gone into the development of the fundamental macroscopic relationships by amongst others, Oeding (1963); Predtechenskii and Milinskii (1969); Polus *et al.* (1983); Ando, Ota and Oki (1988); Daly, McGrath and Annesley (1991); Sarkar and Janardhan (1997); Lam and Cheung (2000); Ye *et al.* (2008) and

Saif (2009). Whilst fundamental curves have been developed for various situation and environments, there is, as stated by Schadschneider *et al.* (2009), still "*no consensus about the origin of the discrepancies between different fundamental diagrams and how one can explain the shape of the function*". It is believed that cultural influences on walking behaviour could be contributing to the differences observed. More detailed discussion of the researched fundamental diagrams is presented in the following sections.

Weidmann (1993); Knoblauch, Pietrucha and Nitzburg (1996); Stucki, Gloor and Nagel (2003); Daamen and Hoogendoorn (2003a - d); Willis *et al.* (2004) and NYC DCP (2006) all showed that pedestrian walking speeds are dependent on the personal characteristics of pedestrians (viz. age, gender, person size, health, etc.), characteristics of the trip (viz. walking purpose, route familiarity, luggage, trip length), properties of the infrastructure (viz. type, grade, environment attractiveness, shelter) and finally, environmental characteristics (i.e. ambient and weather conditions). Besides the exogenous[20] factors, the average walking speed also depends on the pedestrian density as per the macroscopic fundamental relationship discussed in the previous subsection.

Studies comparing the pedestrian flow characteristics of various countries have also been carried out by Pushkarev and Zupan (1975b); Seneviratne and Morrall (1985); Morrall *et al.* (1991); Tanaboriboon, Hwa and Chor (1986); Al-Masaeid, Al-Suleiman and Nelson (1993); Lam, Morrall and Ho (1995); Lam and Cheung (1999) and Finnis and Walton (2007). The results of these studies revealed that pedestrian flow characteristics are generally site and region specific and later studies revealed that planners and engineers should take into account the local pedestrian flow characteristics when planning for pedestrian facilities.

This was further supported when comparisons of pedestrian flow characteristics between Western (Canadian) and Asian cities were made resulting in the comment by Morrall *et al.* (1991) that "*different geographic areas yield different walking speeds"* and that *"pedestrian planning should be based on local pedestrian characteristics rather than on pedestrian characteristics from cities with dissimilar cultures*."

In 1971, Fruin observed that luggage significantly impacted on average free-flow speeds. More recent work (cf.) by Davis and Braaksma (1988); Willis *et al.* (2004) and NYC DCP (2006) however revealed that the average free-flow speeds of baggage-laden pedestrians are not significantly different when compared to the free-flow speed of the un-laden pedestrian. The "self-selection" effect must however be considered in this finding, where individuals who are healthy and fit are the ones who are perhaps more likely to travel with heavy baggage. Thus, if baggage-laden pedestrians have about the same speed as un-laden pedestrians, it may simply be that fitter ones travel with baggage, rather than walking with baggage does not slow down pedestrian walking speeds. Furthermore, very heavy and bulky luggage would clearly be an influence on walking behaviour and that the results of the research referenced, although not clearly defined, assume normal baggage of reasonable weight and size.

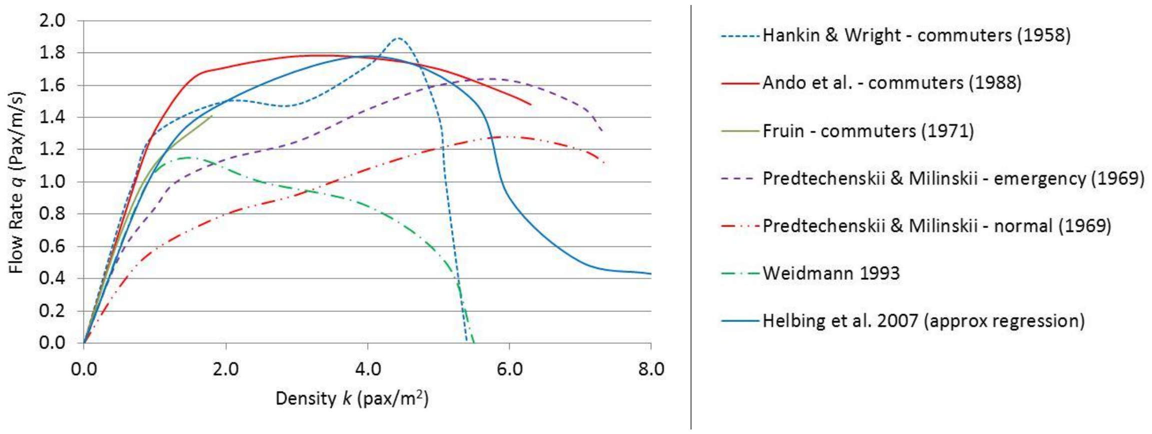
Whilst most empirical studies observed uni-directional flows, work by Lam *et al.* (2003) revealed that different bi-directional flow ratios significantly impacted on the at-capacity speed and flow rates and found that the more unbalanced the flow rate, the greater the impact on overall capacity and speed. These observations were confirmed by Wang and Liu (2006) using the results of a pedestrian simulation exercise.

For pedestrian flow parameters of various walking facilities, Virkler and Elayadath (1994) found that the relationship between pedestrian flow, density and speed is similar to that for vehicle flow parameters, where the pedestrian flow increases with increasing density and then decreases rapidly after the density exceeds a critical value and speed maintains a downward trend with increasing density.

Johnson (1977) however mentioned that it is rare that a density which reduces flow (after the optimum flow has been reached) ever occurs in practice and suggested that capacities can be assumed to be directly proportional to density. Recent research by Ye *et al.* (2008) has however validated the consistent macroscopic relationship of traffic flow parameters for pedestrians and seems to support the observation made by Johnson.

Schadschneider *et al.* (2009) point out that "*no consensus has yet been achieved about the basic quantitative properties of pedestrian behaviour*" which is manifested in the fact that the shape of the fundamental diagrams differ for various facilities like walkways, stairs or ramps. Reasons for deviations to the fundamental diagrams are suggested by several researchers and is attributable to; cultural differences (Morall *et al.* (1991); Helbing, Johansson and Al-Abideen 2007), uni- or multidirectional flows (Navin and Wheeler 1969; Pushkarev and Zupan 1975a; Lam *et al.* 2003), type of traffic incorporating shoppers, commuters etc. (Oeding 1963), type of environment (Kockelman 2000) and time of day (Willis *et al.* 2004).

Figure 2.5 provides a comparison of the various flow rate (*q*) versus density (*k*) relationship plots developed by various researchers for level terrain. Helbing *et al.* (2007) specifically argue that cultural and population differences are responsible for deviations between the Weidmann (1993) data and their data shown in the figure.

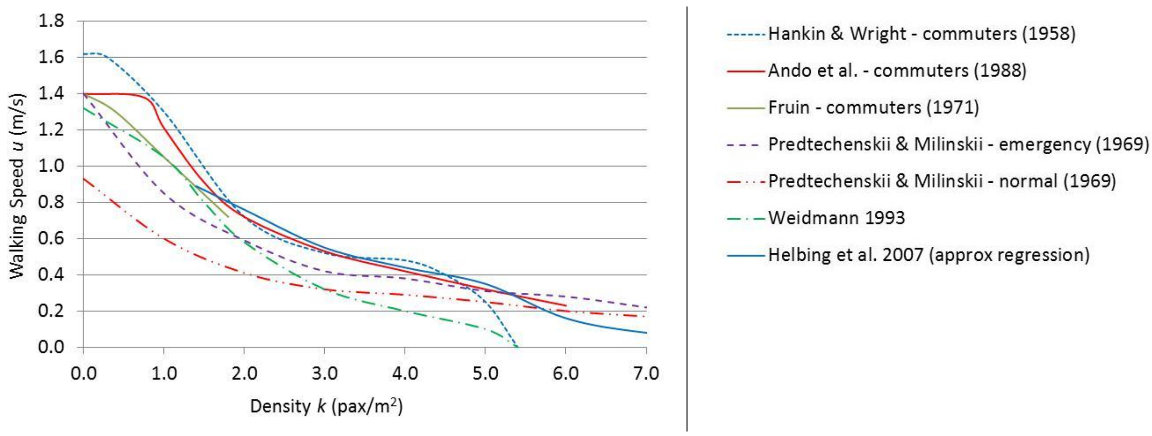


Note: The relationship by Helbing et al. (2007) is an approximated regression curve fitted to the data points of their experimental measurements.

Figure 2.5: Relationship between flow rate (*q*) vs. density (*k*); (Source: Thompson 2004; Schadschneider *et al.* 2009)

Weidmann (1993) collected data from 25 datasets but neglected differences between multi and uni-directional flows in his diagrams but nevertheless concluded, in accordance with Fruin, that there are only minor differences between the diagrams for these flows. By visual observation of Figure 2.5, this statement can generally be considered acceptable for density (*k*) values less than 1.0 pax/m^2 but, as the figure shows, significant variation in the relationships occur at densities exceeding 2.0 pax/m^2. It is interesting to note that relatively few datasets, except the data by Hankin and Wright, Weidmann and Helbing *et al.* had data points continuing well past the critical density (q_c) point.

Fundamental relationships between walking speed (u) and density (k) for various datasets over level terrain, including the observations made by Fruin (1971) and Hankin and Wright (1958) are shown in Figure 2.6 below.



Note: Fruin curve not projected beyond 1.8 pax/m^2 due to lack of data.

Figure 2.6: Relationship between speed (*u*) vs. density (*k*) ; (Source: Thompson 2004; Schadschneider *et al.* 2009)

The resulting plotted relationships show that the walking speed (u) versus density (k) relationship is not always a linear relationship, but follows a particular s-curve shape for most relationships. The same result was documented from observations on a sidewalk in Tannenstrasse, Zürich by Gloor, Mauron and Nagel (2003), (not plotted), who found that the u vs. k relationship is not linear and followed a similar s-shaped curve.

2.3.4 Towards a Fundamental Flow Rate Equation

There have been several researchers who have used regression relationships for the prediction of pedestrian flows for specific environments. Table 2.3 provides a chronological list of researchers and the regression equations applied to the macroscopic fundamental relationships observed.

Table 2.3: Summary of proposed MFD relationships; (Source: Daamen 2004)

Source	Sample Environment	Data Collection Method	Relationship
Older (1968)	Shopping Streets: Oxford Street, London and High Street, Slough (UK)	Based on cine camera recordings (taken at 10 frames per second). Frame rate checked by recording stopwatch within video frame.	$u = 1.31 - 0.34k$ $q = 1.32k - 0.34k^2$ $q = 3.85u - 2.94u^2$
Navin & Wheeler (1969)	University of Missouri campus and Stephen's college (sidewalks only)	Time-lapse colour photography, taken at 4 frames per second from an elevated position.	$u = 2.13 - 0.79k$ $q = 2.13k - 0.79k^2$ $q = 2.70u - 1.27u^2$
Fruin (1971)	Peak-hour flows at a large commuter bus terminal	Manual counting, stopwatch timing and still photography.	$u = 1.43 - 0.35k$ $q = 1.43k - 0.35k^2$ $q = 4.08u - 2.86u^2$

Table 2.3: Summary of proposed MFD relationships; (Source: Daamen 2004)

Source	Sample Environment	Data Collection Method	Relationship
Tanaboriboon *et al.* (1986)	Singapore	Based on manual observations of controlled experiments using time-lapse photography or video recordings.	$u = 1.23 - 0.26k$ $q = 1.23k - 0.26k^2$ $q = 4.73u - 3.85u^2$
Pauls (1987)	Stairs (in total evacuation of tall office buildings)	Data collected over 30 evacuation drills in highrise office buildings using participant-observers, video and audiotape recordings.	$u = 1.26 - 0.33k$ $q = 1.26k - 0.33k^2$ $q = 3.82u - 3.03u^2$
Lam *et al.* (1995)	Indoor walkway in Hong Kong	Video recording, with semi-automatic data extraction collected over 1 minute intervals.	$u = 1.29 - 0.36k$ $q = 1.29k - 0.36k^2$ $q = 3.58u - 2.78u^2$
Sarkar & Janardhan (1997)	Calcutta Metropolitan transfer area	All data collected manually at various time intervals using a 10 m long "trap" length.	$u = 1.46 - 0.35k$ $q = 1.46k - 0.35k^2$ $q = 4.17u - 2.86u^2$
Klüpfel *et al.* (2002)	Average of several walkway and passageway	Taken from data observed by Weidmann (1992) built over an average of 58 single studies.	$q = 1.34 \times k\,(1\text{-}e^{-1.93(1/k-1/5.4)})$
Saif (2009)	Holy Mosque, Khalid Bin Alwaleed Rd, Makkah, Saudi Arabia	Video recording. Grid marked sheet was then attached to the video screen to count varables on scene playback.	$u = 65.57 – 21.14k$ [m/min] $q = 65.57k – 21.14k^2$ [ped/m/min] $q = 3.103u – 0.0473u^2$

Units: k [Pax/m^2]; u [m/s]; q [pax/m/s] unless otherwise stated

Instead of using quadratic regression equations, Daganzo and Geroliminis (2008) simplified the representation of the *q* vs. *k* MFD relationship by utilising a series of three linear equations to approximate the bell curvature.

It is noted that most of these studies reported a non-linear relation between speed and density. The linearity of the speed-density relation has long been questioned for pedestrian flows (Pushkarev and Zupan 1975a) and the previous subsection has shown that an s-curve relationship appears to be more prevalent.

Even though the regression equations shown in the table above appear relatively simple, the exact relationships between speed, density, flow and width can vary depending upon the situation in question and there can also be many influences on each element and therefore the capacity of any given relationship.

The influences on flow rate and capacities are not something fully agreed upon by the research community and the main influences on the fundamental pedestrian dynamic is discussed further in Section 2.4.

2.3.5 Fundamental Pedestrian Dynamic on Level Terrain

Table D4 in Appendix D summarises characteristics of capacity flow conditions on level terrain, including jam density (k_j), capacity density (k_c) and capacity flow rate (q_c) together with the associated speed at the capacity flow rate (u_c), as found by various researchers. Figure 2.7 shows the flow rate capacity (q_c) results of some 24 measurement experiments conducted worldwide since 1958.

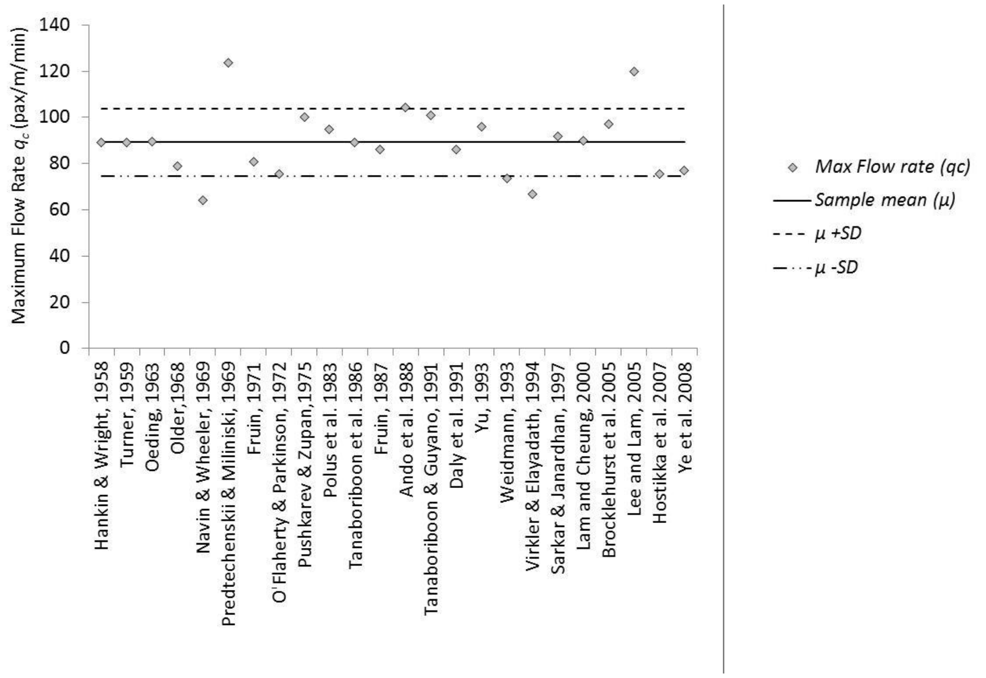


Figure 2.7: International capacity flow rates (q_c) observed on level terrain for various level infrastructure types

From the international research data plotted in Figure 2.7, an average (μ) maximum flow rate capacity (q_c) of 89.19 pax/m/min is obtained with a standard deviation (SD) of 14.52 pax/m/min. The highest flow rate capacity (q_c) observed is 123.6 pax/m/min recorded by Predtechenskii and Miliniskii (1969) in Russia. The lowest flow rate capacity (q_c) observed is 64.0 pax/m/min recorded by Navin and Wheeler (1969).

Hankin and Wright (1958) studied passenger flows in subways in the United Kingdom and observed a maximum flow rate (q_c) for level routes of 89 pax/m/min at a capacity density (k_c) of 1.4 pax/m^2.

From studies of uni-directional commuter flow on walkways, Fruin (1987) observed maximum average peak flow rates (q_c) of 86 pax/m/min at a capacity density (k_c) of approximately 2.2 pax/m^2.

Turner (1959), Ando *et al.* (1988), Daly *et al.* (1991) and Lam and Cheung (2000) studied pedestrian movement at fully loaded rail stations and (apart from Ando *et al.*) also found capacity flow rates (q_c) to be between 86 to 92 pax/m/min, but at capacity densities (k_c) at around 1.4 pax/m^2. Ando *et al.* found a significantly higher capacity flow rate (q_c) at 101 pax/m/min at a much higher capacity density (k_c) of 4.5 pax/m^2. Lee and Lam (2005) conducted pedestrian observations at a Hong Kong railway station and found an even higher capacity flow rate (q_c) of 120 pax/m/min. The higher flow rates observed by Ando *et al.* (1988) and Lee and Lam (2005) at Japanese and Hong Kong stations respectively could be attributed to the smaller Asian physique who are accustomed to such crowded conditions and who are likely to accept smaller inter-person buffer spaces contributing to the higher capacities observed.

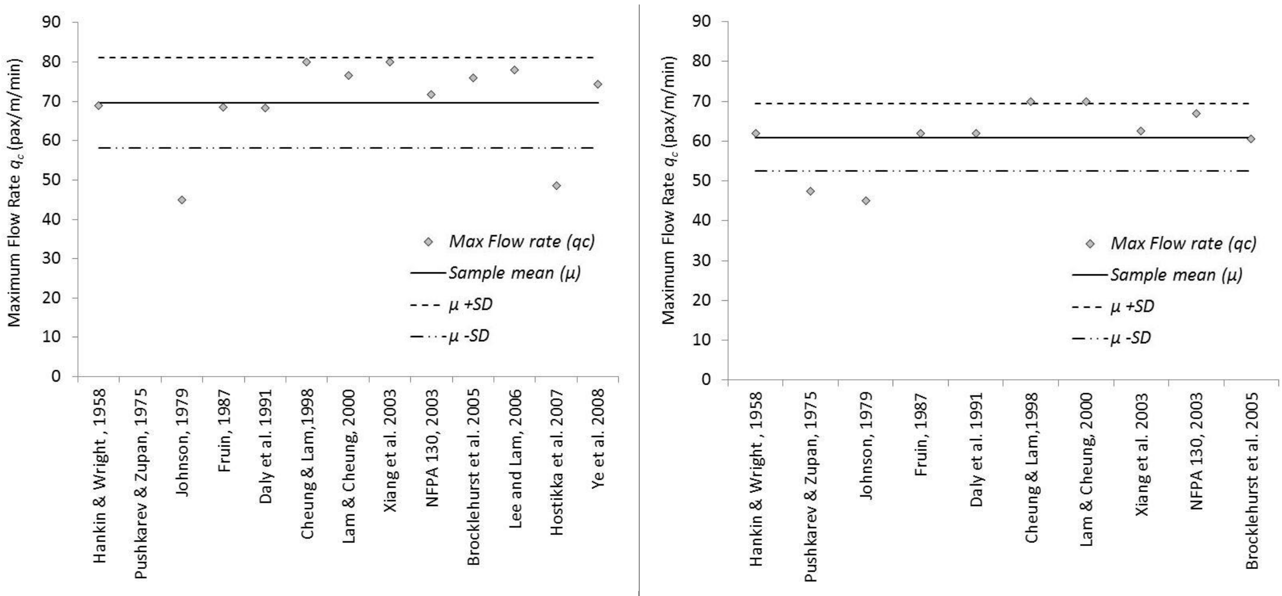
A literature study by Milazzo *et al.* (1999) concluded that flow rate capacities (q_c) ranged from 72 pax/m/min for American facilities to around 90 pax/m/min for Asian facilities, which, although not as high as the result observed by Ando *et al.* (1988) and Lee and Lam (2005), supports the notion that culture effects play a large role in pedestrian dynamics.

From Table D4, Jam density (k_j), defined in Subsection 2.3.2, appears to be between 4.0 and 5.5 pax/m^2, whereas only AlGadhi, Mahmassani and Herman (2001) show a significantly higher jam density (k_j) of 7.0 pax/m^2, which is inherent to the conditions in which the density was measured, namely during a yearly stone throwing ritual by pilgrims in Makkah, Saudi Arabia, where pedestrians do not have the intention to walk, but to complete the stone throwing ritual.

From the table (and Figure 2.7), the range of observed capacity flows (q_c) appears to be between 75 and 100 pax/m/min using ($\mu \pm$ SD) as the indicative range of values. The range in capacities is attributable to walking conditions or scenarios, for example lower capacities are observed after a football match (SCICON 1972), whereas high capacities are found in transfer stations as per the observations of Ando *et al.* (1988). Very low capacity flow rates (q_c) of less than 50 pax/m/min (not plotted) has been observed by Brocklehurst *et al.* (2005a); Brocklehurst *et al.* (2005b) and Saif (2009) but these observations were conducted at a stadium, educational institution and on a road sidewalk respectively, not normally associated with urgent pedestrian behaviour.

2.3.6 Fundamental Pedestrian Dynamic on Stairs

Table D3 in Appendix D summarises capacity flow conditions on stairways, including capacity flow rates (q_c), capacity density (k_c) and critical speed[14] (u_c), viz. the associated speed at the capacity flow rate, as observed by various researchers worldwide. Figures 2.8 (*a.*) and (*b.*) shows the flow rate capacity (q_c) results of n = 12 and n = 10 independent measurement observations for the descending and ascending direction respectively.



(a.) Descending direction (n = 12) *(b.) Ascending direction (n = 10)*

Figure 2.8: International capacity flow rates (q_c) observed on stairs

From the descending data plotted in Figure 2.8 (*a.*), an average (μ) maximum flow rate capacity (q_c) of 69.67 pax/m/min is calculated with a standard deviation (SD) of 11.49 pax/m/min. This is higher than the average (μ) maximum flow rate capacity (q_c) for the ascending direction at 60.87 pax/m/min, with a standard deviation (SD) of 8.44 pax/m/min. The 12.63% difference between flow rate capacities is however statistically insignificant at the α = 5% level of significance (t–statistic = 2.01 < $t_{1-\alpha/2,n-1}$).

Earlier studies also show that capacity flow rates (q_c) do not differ significantly with approximately an 11% difference between descending and ascending stair capacities reported by Hankin and Wright (1958); Fruin (1987) and Daly *et al.* (1991), with capacity flow rates (q_c) of approximately 62 and 69 pax/m/min reported for ascending and descending directions respectively.

More recent staircase observations specifically conducted within Asian train station environments done by Cheung and Lam (1998); Lam and Cheung (2000); Xiang, Kok Wai and Hoong Chor (2003); Lee and Lam (2005) and Ye *et al.* (2008) have however revealed more significant differences of between 16% to 22% between the ascending and descending capacity flow rates (q_c). The results of their observations are shown in Table 2.4.

Table 2.4: Staircase flow rate capacities (q_c) observed at Asian railway stations; (various sources)

Source	Year	Location	Capacity Flow Rate q_c (pax/m/min)	
			Ascending	**Descending**
Cheung & Lam	1998	Six stations, Hong Kong	70	80
Lam & Cheung	2000	Two stations, Hong Kong	70	73 – 80
Xiang *et al.*	2003	Singapore	Not observed	80
Lee & Lam	2006	Two stations, Hong Kong	67	78
Ye *et al.*	2008	Shanghai, China	60.6	74.4
		Average q_c	66.9	77.8

Within the National Fire Protection Association Handbook (NFPA 130 2003), which is the standard to be proposed (by the author) in South Africa, the design evacuation flow rates stipulated are 62.6 pax/m/min and 71.7 pax/m/min for the ascending and descending directions respectively, offering a 5 to 10% safety margin over the average overall capacity values (q_c) determined in Table 2.4.

The research by Pauls (1980), documented in the SFPE Handbook (Society of Fire Protection Engineers *et al.* 1995), shows significantly varying capacity flow rates (q_c) from as low as 43 pax/m/min to an optimum value of 71 pax/m/min in staircases of multi-storey buildings. Pushkarev and Zupan (1975b) also did their own studies on movement up subway stairs where capacity flow rates (q_c) were found to range from 42 pax/m/min to 53 pax/m/min.

It should be noted that the above studies are mainly confined to uni-directional flow characteristics. The impacts of bi-directional pedestrian flow characteristics on staircase flow capacity with varying bi-directional flow ratios is discussed in greater detail in Subsection 2.3.8.

2.3.7 Pedestrian Walking Speed on Level Terrain

This subsection will describe the average free-flow walking speeds ($\bar{u}_f$) and pedestrian flow capacity (q_c) measurements for level terrain identified from the literature review and highlights to what extent they are influenced by various factors. Before documenting these results, it is important to understand that the reporting of observed pedestrian walking speeds (u) in the form of a distribution or histogram needs to be qualified (or restricted) to a within particular density level or range due to the fundamental speed (u) vs. density (k) relationship. This lack of clarification was an obvious shortcoming found in much of the literature. For the purpose of this literature review, free-flow walking speed is defined to occur within the LOS A and B density conditions.

Average free-flow walking speeds ($\bar{u}_f$) from 49 international sources for various infrastructure types (viz. street sidewalks, sport stadia, pedestrian paths etc.) as tabulated in Table D5, Appendix D, were obtained and plotted as shown in Figure 2.9.

From the data plotted in Figure 2.9, an average (μ) free-flow walking speed ($\bar{u}_f$) of 1.36 m/s is obtained with a standard deviation (SD) of 0.13 m/s.

As stated previously, free-flow walking speeds (u_f) occur at relatively low densities in the region of 0.4 to 0.5 pax/m^2 or less according to Fruin (1987) and Daamen (2004). At such low densities, work by Tregenza (1976); Henderson (1971); Fruin (1987); Still (2000) and Helbing *et al.* (2001a), found that walking speeds within sample groups follow a normal distribution with the mean changing more than the standard deviation between samples.

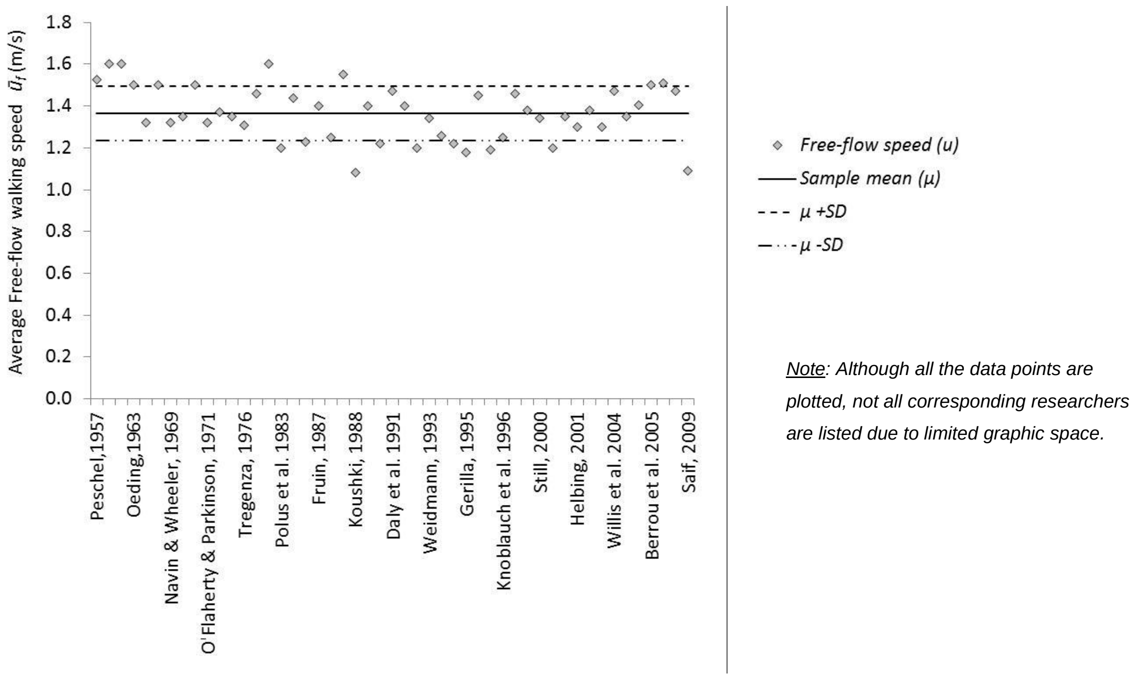


Figure 2.9: International average free-flow speeds ($\bar{u}_f$) observed on level terrain

Studies examining walking speeds for pedestrian facilities have focused primarily on pedestrian flow characteristics in urban settings such as sidewalks, footbridges, shopping centres (Polus *et al.* 1983; Morrall *et al.* 1991; Lam *et al.* 1995; Virkler 1998; Lam and Cheung 2000; Pachi and Ji 2005), transportation terminals (Fruin 1971; Lam *et al.* 1995; Young 1998; Lam and Cheung 2000), and crossing times for crosswalk intersections (Lam *et al.* 1995; Knoblauch *et al.* 1996; Fugger *et al.* 2000; Lam and Cheung 2000; Bennett, Felton and Akçelik 2001; Tarawneh 2001). The free-flow walking speed data for level terrain from the various research sources is tabulated chronologically from 1957 to 2010 in Table D5 attached in Appendix D. From the table, a number of variations in free-flow speed is observed:

Certain observations surveyed are for street crossings viz. Peschel (1957); Henderson (1971); Coffin (1993); Bennett *et al.* (2001); Teknomo (2002) and Matsumoto *et al.* (2010). Apart from Coffin who only measured elderly persons (> 60 years old), the results of these observations show relatively high free-flow walking speeds ($\bar{u}_f$) of between 1.6 m/s and 1.85 m/s and it is assumed that the sample of pedestrians observed were likely to be in somewhat of a rush to cross the road. Studies of street crossing speeds are however likely to display slightly different results, because of oncoming vehicles and impending signal change prompting pedestrians to move faster.

Other observations conducted on street pavements (alongside roads or streets) by Older (1968); Polus *et al.* (1983); Tanaboriboon *et al.* (1986); Weidmann (1993); Gerilla (1995); Knoblauch *et al.* (1996); Willis *et al.*

(2004) revealed (excluding data for elderly persons) a range of free-flow walking speeds ($\bar{u}_f$) of between 1.10 m/s to 1.51 m/s, noticeably lower than the range found for street-crossings identified above. Jordaan and Joubert (1983) also found an average walking speed ($\bar{u}$) of 1.44 m/s in South African cities. Older (1968) noted that most of the people surveyed on city streets were shoppers and therefore it is reasonable to assume that they were not in a rush and there may have been a high percentage of women within the flow. This is assumed to be the reason why the free-flow speeds ($\bar{u}_f$) of between 1.0 m/s to 1.4 m/s observed by Older are relatively low.

Observations conducted within train station environments have been undertaken by Hankin and Wright (1958);Turner (1959); Fruin (1987); Ando *et al.* (1988); Lam and Cheung (2000); Berrou *et al.* (2005); Finnis and Walton (2007) and Ye *et al.* (2008). Apart from the earlier results by Hankin and Wright (1958) and Turner (1959) who recorded average speeds ($\bar{u}$) of 1.6 m/s, the range of walking speeds recorded by the other researchers were found to be between 1.3 and 1.55 m/s. The higher average walking speeds observed by Ando *et al.* (1988) ($\bar{u}$ = 1.4 m/s) and Berrou *et al.* (2005) ($\bar{u}$ = 1.55 m/s) appears to be due to the fact that this work was carried out at a Japanese station and London Clapham Station (UK) respectively, where people may be more experienced/comfortable moving at higher person densities. It is more difficult to be certain about the earlier work by Hankin and Wright (1958) and Turner (1959) because it is unclear whether the pedestrians observed had a more pressing trip purpose (due to the relatively higher walking speeds observed) at the time of being surveyed than the more recent work.

Other more specific observations on rail station platforms and concourses were conducted by Lam and Cheung (2000) and Daamen and Hoogendoorn (2004). Lam and Cheung found overall average platform walking speeds ($\bar{u}$) to be between 1.24 m/s to 1.27 m/s but Daamen and Hoogendoorn found alighting pedestrian walking speeds to be 1.35 m/s and boarding pedestrian walking speeds to be 0.97 m/s. Lam and Cheung also found that average walking speeds ($\bar{u}$) on the station concourses were in the region of 1.28 m/s to 1.29 m/s.

In terms of design walking speeds provided by the various guideline documents, the Institute of Transportation Engineers (ITE 1969) recommends a 1.2 m/s design speed, the American Association of State Highway Transport Officials (AASHTO 1984) recommends a design walking speed of 1.3 m/s to 1.4 m/s and the Federal Highway Administration (FHWA 1988) recommends a design walking speed (u) of 1.2 m/s. The National Information and Technology Centre for Transport and Infrastructure (CROW 1998) based in the Netherlands, recommends a 1.4 m/s design walking speed. The Chartered Institute of Building Services Engineers Guide D (CIBSE 2008) recommends a design speed of between 1.0 m/s to 1.5 m/s dependant on the likely prevailing design density. The latest *Highway Capacity Manual* (HCM), (TRB 2000) recommends a 1.2 m/s design walking speed if 20% of the target population is younger than 65 years old or a 1.0 m/s design walking speed if 20% of the target population is older than 65 years old.

The *South African Road Traffic Signs Manual* (SARTSM), (DOT 1997) and the *Pedestrian Facility Guideline* documents (DOT 2003) uses the same standards as the HCM (TRB 2000), with the 15th percentile walking speed recommended for design purposes. To make provision for the slower pedestrian, SARTSM propose a 1.2 m/s walking speed for normal operating conditions and 1.0 m/s design walking speed for target populations with significant proportions of elderly or disabled pedestrians. It should be noted that the walking speeds proposed by the SARTSM guidelines are used for the purposes of setting traffic signal timings rather than for public transport spatial assessment.

Free-flow speeds (u_f) observed for the walkways leading to escalators and stairs are found to be lower than those on general walkways (Cheung and Lam 1998). This can be explained by the fact that pedestrians normally decelerate when walking towards the approach to an escalator or stairs. According to Cheung and Lam, the length of stairs also significantly influences the walking speed; the longer the staircase, the lower the walking speed.

Daamen (2004) conducted controlled bottleneck experiments and found that the average walking speed ($\bar{u}$) decreased with increasing density (k) as per the macroscopic fundamental relationship and found that speeds are normally distributed about the mean for all ranges of density conditions. From the observed data, Daamen also found that the variance in average speed ($\bar{u}$) decreases with increasing density as well.

Although there are various influential factors affecting observed walking speeds as reported by several researchers, a comprehensive study undertaken by Willis *et al.* (2004) conducted on CBD sidewalks in Edinburgh and York in the United Kingdom (using a sample n = 2,613 participants) confirmed that age, gender, level of mobility, group size, time of day and location were found to have significant effects on movement preferences. The impacts of some of these factors on walking speed is discussed further below:

a. Variation with Age Group

According to early observations by Peschel (1957) at pedestrian crossings, older and younger pedestrians walk slower than the remainder of the population. He obtained the following average walking speeds ($\bar{u}$):

Sample (men and women) from 6 to 10 yrs old:	1.1 m/s
Sample (men and women) from 13 to 19 yrs old:	1.8 m/s
Sample (men only) below 40 yrs old:	1.7 m/s
Sample (men only) over 55 yrs old:	1.5 m/s

Colclough and Owens (2009) determined the following walking speed profiles, based on the results of a literature review, rather than from their own observations:

Child with adult:	1.19 m/s
Child (< 15 yrs):	1.39 m/s
Young Adult (15 – 30 yrs):	1.47 m/s
Adult (30 – 55 yrs):	1.47 m/s
Older person (>55 yrs):	1.17 m/s
Mean:	1.34 m/s

Observations by Ando *et al.* (1988) in Japanese railway stations also observed that people walk fastest in their early twenties, with older and younger people having slower free-flow walking speeds. From this and other studies (Bowman and Vecellio 1994; Coffin and Morrall 1995), it appears as though walking speed declines with increasing age during adulthood and that, according to Knoblauch *et al.* (1996) and Tarawneh (2001), pedestrians over the age of 65 will have a walking speed approximately 10 m/min slower than the overall average walking speed.

Van As and Joubert (1993) also found that children move faster at 1.6 m/s with older persons moving slower at approximately 1.3 m/s. There are however several studies that indicate that it is not merely age, but a variety of other contributing factors related to age influencing walking speeds, such as:

- Fitness level (Cunningham, Rechnitzer and Donner 1986; Imms and Edholm 1981); walking speed decreases with decreasing mobility level.
- Cautiousness (Wilson and Grayson 1980); walking speed decreases with increasing cautiousness.
- Other problems (Coffin and Morrall 1995); the more problems, the more walking speed decreases.

The measurability of these characteristics are however problematic, in other words age can be observed relatively easy, whereas fitness level or cautiousness cannot be observed directly. Since there is a tendency for people to live longer, increasing numbers of elderly pedestrians are evident in our daily lives, and this includes walking. According to Weidmann (1993), especially in the first 20 years of life, the physical abilities of a person increase rapidly from 40% to 100% of the final abilities.

The walking speed for the 18 to 60 age group is significantly higher than that of the over 60-year age group (Bowman and Vecellio 1994). Several studies including Coffin and Morrall (1995); Fruin (1971); Tanaboriboon *et al.* (1986) and Wilson and Grayson (1980) report walking speeds of between 0.6 and 1.2 m/s for the over 60-year age group, with an average walking speed ($\bar{u}$) of 1.06 m/s and a larger variance than for adults.

Tanaboriboon *et al.* (1986) found that young pedestrians (secondary school children) had a mean walking speed comparable with that of an adult's speed. Observations by Knoflacher (1987) and Weidmann (1993) also revealed that children (of age less than 12 years old) have a much lower walking speed than secondary school children. Willis *et al.* 2004 found the average walking speeds ($\bar{u}$) of under 16-year olds at around 1.53 m/s and the age group between 16 and 64 years old were found to have average walking speeds ($\bar{u}$) in the range of 1.55 to 1.38 m/s (decreasing in proportion to the age in that group) with the over 65-year age group found to have an average walking speed ($\bar{u}$) of only 1.16 m/s. A study on New York City sidewalks (NYC DCP 2006) obtained similar results, where it was found that persons older than 65 years old and younger than 14 years old walked slower at 1.11 m/s when compared to the 14 to 65 year old age group walking at an average walking speed ($\bar{u}$) of 1.31 m/s.

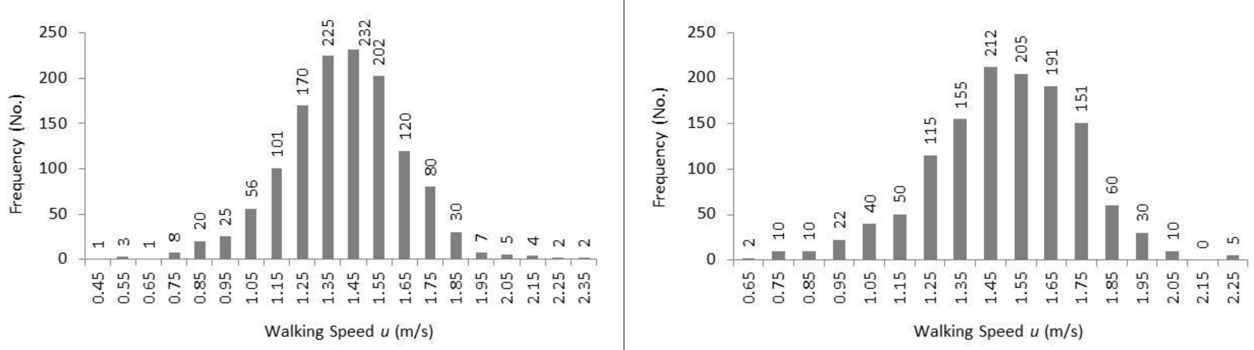
An interesting study conducted by Coffin (1993), where the walking speeds of 184 senior people over the age of 60 were observed at signalised and unsignallised pedestrian crossings, revealed that whilst adult men walked faster than adult females, gender did not play a role in the senior person walking speeds.

b. Variation with gender

It has been found by Boles (1981); Ando *et al.* (1988); Henderson (1971); Peschel (1957); Polus *et al.* (1983); Navin and Wheeler (1969); Knoblauch *et al.* (1996); Tarawneh (2001); Willis *et al.* (2004) and NYC DCP (2006) that women have lower free-flow speeds (u_f) and walk approximately 4 m/min to 5 m/min slower than men, although this is not always the case; see Coffin (1993) in the previous paragraph. Ando *et al.* (1988) showed that male walking speeds ranged from 1.0 to 1.5 times faster than women depending upon the age, while Polus *et al.* (1983) noted a range from 1.07 and 1.12 faster than women.

Weidmann (1993) found an average walking speed ($\bar{u}$) of 1.41 m/s for men and 1.27 m/s for women (a factor of 1.11), whereas Hoel (1968) observed the average walking speed for men at 1.55 m/s and for women at 1.45 m/s (a factor of 1.07) in the Central Business District of Pittsburgh (United States). The fact that Hoel found higher speeds than Weidmann may be due to the different trip purposes of the pedestrians, e.g. commuters versus mixed flows.

In a sample of 2,613 participants observed walking on sidewalks at three different locations in the United Kingdom, Willis *et al.* (2004) observed the average free-flow walking speed ($\bar{u}_f$) of males to be 1.52 m/s versus the 1.42 m/s for women, a factor 1.07, similar to the observations by previous researchers. Figure 2.10 shows the walking speed frequency distribution of their study.



(a.) Females *(b.) Males*

Figure 2.10: Walking speed distribution according to gender (*n* = 2,613); (Source: Willis *et al.* 2004)

A similar study conducted on New York City sidewalks (NYC DCP 2006) confirmed the general consensus that men walk faster (at 1.35 m/s) than women (at 1.25 m/s), a factor difference of 1.08 or 7.4%. The walking speed difference between men and women may be as a result of the different physical characteristics of men and women, which may result in larger step lengths and higher step frequencies for men.

c. Variation with facility width

Researchers have historically debated whether there is a step-wise change in capacity flow rate with width or whether the relationship is linear. According to the work carried out by Pauls (1980) and the overriding number of modern guides, such as *CIBSE Guide D* (CIBSE 2008) and the *SFPE Handbook* (SFPE 1995), a linear relationship is used. Further support for the linear change of flow rate with width is provided by Hankin and Wright (1958), who studied passenger flows in subways and noted that above 1.2 m, maximum flow becomes directly proportional to width.

However, a number of step-wise equations have been carried through into modern design guidance, such as within the *Primrose Guide* (Home Office 1985), where there is still reference to the unit of exit width, stating a flow rate of 40 pax/minute/unit width, with each unit width being 0.525 m. The controlled observations by Daamen (2004) on people flow in bottlenecks also supports a step-wise relationship.

It should be noted that pedestrians tend to keep a buffer zone between themselves and the walkway edge. Habicht and Braaksma (1984) made a study of students walking through a passageway in Carleton University (Canada) to determine these buffer distances and observed that these zones appeared to depend upon wall material with a metal mesh material having smaller buffer depths than rougher concrete walls.

d. Influence of counter flow

Unlike vehicular flow where flow is separated by direction, the phenomenon of counter (or bi-directional) flow is the norm within railway station environments; for example, there may be many people arriving whilst people are departing utilising the same infrastructure e.g. walkways or stairways.

Early studies of commuter flow by Older (1968) revealed that there was no significant reduction in capacity flow rate for any of the bi-directional flows observed. The flow regimes studied were however restricted to 80:20 and 50:50 levels of counter flow. A reduction in effective capacity and walking speed due to opposing pedestrian flow was however reported by Navin and Wheeler (1969) who measured the flow phenomenon of students on pavements. They found that the greatest losses are when there is the highest degree of counter-flow, but reported only a 5% reduction in overall capacity. Later studies by Pushkarev and Zupan (1975b) supported these general findings who indicated that 50:50 bi-directional flows were essentially equivalent to 100% uni-directional flows, although they did comment that "*complications*" occurred when the counter flows were minor.

Fruin (1987) mentioned that "*bi-directional capacity flow rates on sidewalks are not dissimilar to uni-directional capacity flow rates*" and quantified that the difference is least significant at a 50:50 ratio of flow with only a 4% capacity reduction. Fruin also discovered that the most significant reduction in flow rate was observed with 10% of counter-flow, where a reduction of 14.5% in capacity was found.

Cheung and Lam (1997) observed the effects of bi-directional flow on passageways and stairways with an emphasis on flows at capacity conditions. They observed that when the directional distribution of the pedestrian flow was 50:50 (i.e. a flow ratio[d] of r = 0.5), the effective capacity of the passageway for each direction was approximately half the two-way capacity (or reduced by 50%) indicating that pedestrians share the width of the passageway equally. They also reported that reductions in both the walkway capacity and the at-capacity walking speed in the minor flow direction were observed. This reduction increased as the imbalance of directional split of pedestrians increased and found that the bi-directional pedestrian flow effects on the stairways were more significant than those on the passageways under at-capacity conditions. This result by Cheung and Lam challenged the pre-1980's stance that flow ratio did not affect capacity significantly.

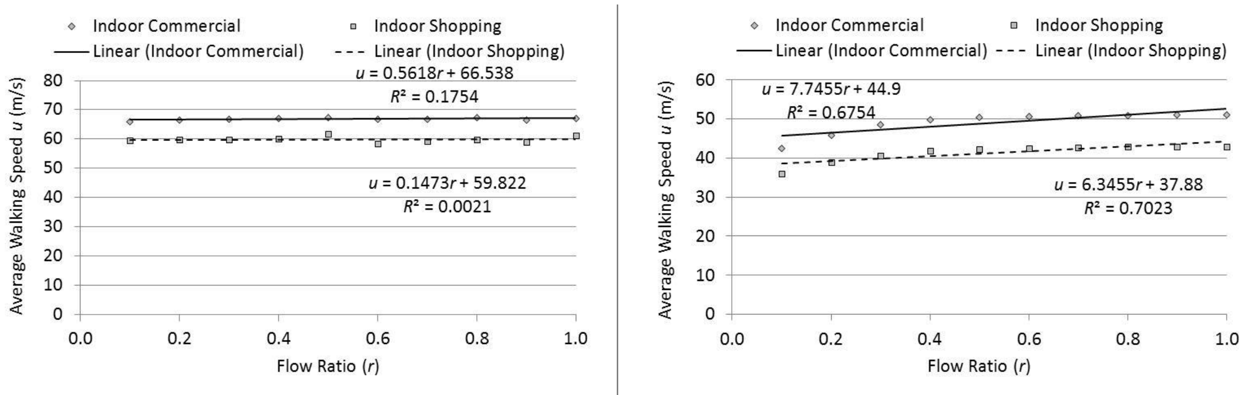
[d] *The flow ratio (r) is the proportion of one-way pedestrian flow of the total two-way pedestrian flow.*

The concept that capacity and walking speed reduces with reducing flow ratio values (*r*) gained further support through microsimulation experiments conducted by Blue and Adler (1999) who used a cellular automata model to simulate the bi-directional flow mechanism. Blue and Adler's experiments were conducted over a range of directional splits from 100:0 to 50:50 and found that the emergent flow vs. density curves were virtually identical to the results of the uni-directional case, with a worst case 90% capacity reduction observed for the 90:10 split.

When the number of pedestrians on a walkway face little opposing flow (i.e. $r > 0.5$), they have more freedom to choose their walking speeds and easily overtake other people on the walkway. However, when pedestrian flow in the opposing direction is heavy (i.e. $r < 0.5$), they then have less freedom to choose their walking speeds as it is not easy to bypass other pedestrians. Thus, the effective capacity of a walkway and the walking speeds of the pedestrians will be reduced when the opposing pedestrian flow increases and becomes significant when the pedestrian flows are close to the capacity of the walkway. However, where bi-directional flow is concerned, a number of researchers including Helbing *et al.* (2001a), Blue and Adler (2001) and Still (2000) have observed "*self-organising*" channels (also referred to as "*streaming*") which naturally occurs to maximise the efficiency of the flow. Pedestrians can see each other coming and defer to one side or the other. Pedestrians then follow those going in the same direction and channels form. According to Weidmann (1993), the formation of lanes is the main reason for the relatively small loss of flow capacity in the case of bi-directional pedestrian flows.

More recently, Lam *et al.* (2003) conducted observations on walkways in Shatin (a shopping area) and Wan Chai (a commercial area) which however confirmed Fruins original findings that bi-directional flow ratios have significant impacts on both the at-capacity walking speeds and the maximum flow rates of the selected walkways. For a 10% counterflow, Lam *et al.* observed a 16.5% capacity drop for both datasets.

Lam *et al.* also studied variations of the walking speed for the indoor walkways for shopping and commercial areas under different flow ratios and density conditions. Despite the observation that walking speeds for indoor walkways (in commercial areas) were observed to be higher than those in shopping areas, it was also observed that there was no significant difference between the walking speeds under various flow ratios (*r*) for the free-flow; refer to Figure 2.11 (*a.*) and a slight increase in walking speed with increasing *r* for the at-capacity conditions; refer to Figure 2.11 (*b.*).



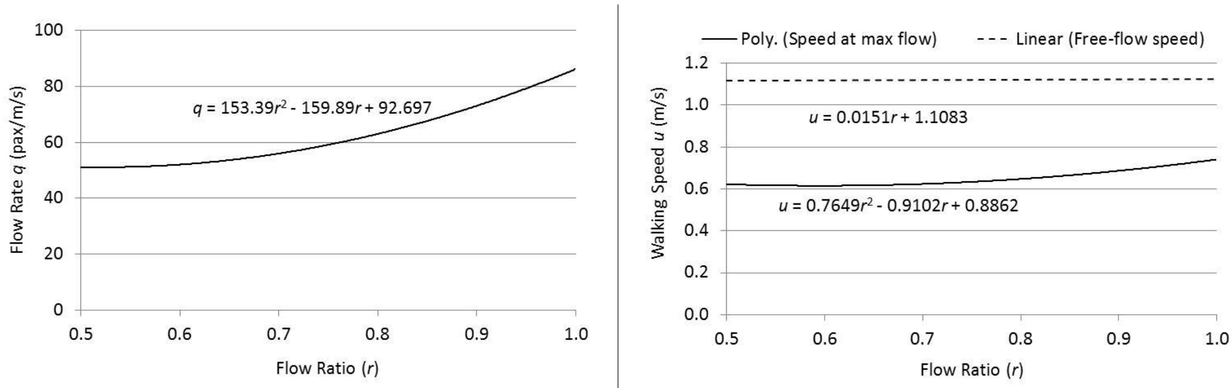
(a.) Free-flow conditions *(b.) At-capacity conditions*

Figure 2.11: Relationship between walking speed (*u*) and flow ratio (*r*); (Source: Lam *et al*. 2003)

Wang and Liu (2006) conducted a simulation exercise with varying counterflow proportions as indicated in Table 2.5 and plotted in Figure 2.12 (*a.*) and (*b.*). From Figure 2.12 (*a.*), when the flow ratio (r) decreased from 1.0 to 0.5, the flow rate (q) decreased from 86.77 pax/m/s to 50.55 pax/m/s, a drop of 41.7% which corroborates with the 50% drop at r = 0.5 observed by Cheung and Lam (1997). Wang and Liu observed a capacity drop of 16.4% at r = 0.9 which is supported by similar findings by Hoogendoorn *et al*. (2007) who observed capacity reductions of up to 15% when flow directions are not evenly distributed (i.e. at r = 0.9).

Table 2.5: Simulation results for different flow values; (Source: Wang & Liu 2006)

Description	**Flow ratio (*r*)**					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
Maximum flow (pax/m/min)	50.55	52.77	56.39	62.58	72.50	86.77
Free-flow walking speed (m/min)	67.12	66.87	66.95	67.42	67.34	67.38
Walking speed under maximum flow (m/min)	37.2	37.2	37.4	38.7	41.2	44.5



(a.) Flow rate (q) vs. flow ratio (r) *(b.) Walking speed (u) vs. flow ratio (r)*

Figure 2.12: Function of flow rate (*q*) and walking speed (*u*) at various flow ratios (*r*); (Source: Wang & Liu 2006)

From the results plotted in Figure 2.12 (*b.*), they found that flow ratio (r) had no effect on free-flow walking speed (u_f) but they observed a small increase in speed (u) with increasing flow ratio (r) for at-capacity conditions. This supports the earlier findings of Lam *et al*. (2003).

Unlike on level walkways, a minor pedestrian flow in the opposing direction on a stairway can result in a capacity reduction disproportionate to the magnitude of the reverse flow. According to the TCQSM (TRB 1999c), a small reverse flow should be assumed to occupy one pedestrian lane or 0.75 m of the stair's width. For a stair 1.5 m wide, a small reverse flow could therefore consume half its capacity.

e. Influence of incline

Fruin (1987) found that there was no change in walking speeds (u) for gradients up to 6%. At a gradient of 10%, Fruin found an 11.5% reduction and at a 20% gradient, he observed a 25% reduction in walking speed. Similar to the findings by Fruin (1987) in relation to free-flow walking speeds, the Fire Protection Handbook (NFPA 130 1997) references independent work conducted on London subways, where it was observed that gradients of up to 6% had no effect on flow rate. There were no further comments for other gradients.

Colclough and Owens (2009) determined the following average speed ($\bar{u}$) profiles, based on the results of an intensive literature review: (Note that the results are average results incorporating a mixed sample viz. commuter, non-commuter, adult with child and older person demographic profile).

Gradient < 2^{o}: 1.47 m/s
Gradient < 4^{o}: 1.39 m/s
Gradient < 5^{o}: 1.53 m/s
Gradient < 6^{o}: 1.53 m/s
Gradient < 7^{o}: 1.39 m/s

f. Summary Discussion

In summary, the common findings of most of the studies reviewed in this subsection show that women generally walk slower than men and that people over 65 years of age walk slower than their younger counterparts. Table 2.6 shows the results of minimum, average and maximum values of free-flow walking speeds and flow rate capacities observed across all the studies reviewed.

Table 2.6: Summary results of free-flow walking speed and flow rate capacities for level and stair terrain

Criteria	Level terrain		Stairs	
	Free-flow walking speed (u_f) (m/s)	Flow rate capacity (q_c) (pax/m/min)	Descending flow rate capacity (q_c) (pax/m/min)	Ascending flow rate capacity (q_c) (pax/m/min)
Minimum value	1.08	74.67	45.00	45.00
Average value	1.36	89.19	69.68	60.87
Maximum value	1.60	103.71	80.00	70.00

2.3.8 Pedestrian Walking Speed on Stairs

In South Africa, stairs play a prominent role in the transition between grade-separated infrastructure. They present particular challenges for younger children, people with disabilities and older adults where 10 to 15% of all falls by the elderly involve stairs (Pauls 2004; Coutts, Lockett and Edwards 2005). Behaviour attributes such as social and cultural aspects also play a role in stair behaviour (Nicoll 2007).

The free-flow speed data observed for stairways by Fruin is tabulated in Table D1 (Fruin 1971) and from various other authors is tabulated in Table D2 in Appendix D. From the tables, a number of variations to free-flow speed is documented. Note that some authors present speed in terms of either slope speed or as a horizontal vector speed. Some of the more important literature findings on stair movement are commented on as follows:

1. In his research on commuter movements, Fruin (1987) found that horizontal speeds of locomotion on stairs displays a close relationship with riser height, with the faster speeds for both ascending and descending movement occurring at lower riser heights. Fruin also discovered that age and gender lead to a different distribution of speeds. A seminary survey of over 700 people gave the results tabulated in Table D1. The overall average free-flow (slope) speed for the descending direction was found to be

approximately 0.82 m/s.

As can be observed in Table D1, changes in riser and tread dimensions do have an effect on the speed of movement. A question of whether it is the angle of the stair or the tread dimension that changes the speed is also partly answered by Fruin's work in that there is only a small change in tread for a significant change is speed. From the work by Fruin, we can confidently state that gradient is the significant contributing factor impacting on speed.

2. An extensive study by Fujiyama and Tyler (2004) involving students and staff at the University College, London supports the findings of Fruin and found linear decreasing (horizontal) stair speeds with increasing gradients. They also found speeds to be faster in the descending direction with increasing differences between the ascending and the descending direction (from 6.5% to 22%) with increasing stair gradients from 24.6^o to 38.8^o. Also from their observations, it was found that the more men present and the more people between 30 to 50 years of age, the faster the stair speeds observed.

3. Several staircase observations have been conducted within railway station environments by Cheung and Lam 1998; Lam and Cheung 1999; Xiang *et al.* 2003; Daamen and Hoogendoorn 2004; Berrou *et al.* 2005 and Ye *et al.* 2008. Cheung and Lam found descending horizontal speeds to be 0.97 m/s and ascending speeds to be 0.86 m/s at six stations in Hong Kong (a difference of 11.3%). Ye *et al.* (2008) also found descending slope speeds to be faster than ascending speeds in a Shangai metro station, but with a higher 18.5% speed difference.

   Berrou *et al.* (2005) found that average ascending speeds for London commuters (0.74 m/s) was higher than the Hong Kong commuter descending speed (0.71 m/s). This observation was attributed to the smaller physique of Asians and shorter leg length gait. Generally, the ascending walking speeds on stairways will always be lower than on those descending as the energy expended in the former condition is greater than that expended in the latter.

4. Daamen and Hoogendoorn (2004) conducted observations at Delft station in Holland and found average horizontal ascending speeds of 0.70 m/s and horizontal descending speeds of 0.75 m/s.

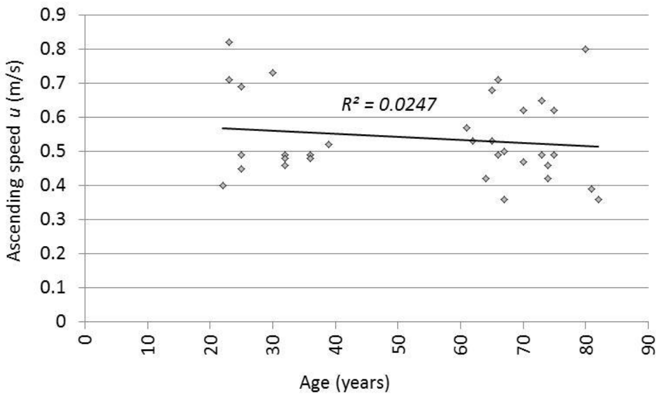
5. For free-flow speeds on stairs, Pauls, in the Society of Fire Protection Engineers *et al.* (SFPE 1995) observed a 0.8 m/s average horizontal descending speed. Hankin and Wright (1958), who studied passenger flow in subways, also observed an unimpeded (free-flow) average speed of 0.8 m/s for ascending pedestrians and 0.98 m/s for descending pedestrians.

6. Kretz *et al.* 2008 conducted observations on stairs at the Dutch Pavilion at the Expo 2000 in Hannover, Germany, where the speeds of 485 persons were observed. Horizontal stair speeds of between 0.36 m/s and 0.42 m/s were found from a high density situation to unimpeded flow conditions. Note that the low speeds observed indicate a more leisurely trip purpose.

7. According to findings by van As and Joubert (1993), the average horizontal walking speed on stairs is affected by riser height and is approximately 0.5 m/s when climbing and approximately 0.6 m/s when descending.

a. Variation with Age Group

Although the study by Fujiyama and Tyler (2004) showed speed differences between certain age groups, viz. 30 to 50 and over 50 years old, their study showed no correlation of stair speeds to age, height and/or weight of pedestrians. Figure 2.13 shows the poor correlation (R^2 = 0.0247) calculated between ascending stair speeds and age. The *P*-value revealed an insignificant relationship at the α = 5% level of significance.



Summary Statistics:
Sample n = 33
R^2 = 0.0247
P-value = 0.383
t-statistic = -0.885

Figure 2.13: Scatter plot showing poor R^2 between ascending horz. speed & age; (Source: Fujiyama & Tyler 2004)

b. Variation with gradient

The horizontal speed on slopes depends on the gradient and walking speeds observed vary between 1.19 m/s and 1.66 m/s in the ascending direction. On declines, the horizontal speed increases slightly between 1.41 m/s and 1.51 m/s (ITE 1969). Pauls (1987) and Weidmann (1993) measured ascending speeds to be between 0.61 m/s and 0.9 m/s but found that the speed decreases to 0.70 m/s for walking downwards on stairs. Weidmann (1993) and Ladetto *et al.* (2000) found that pedestrian speeds are slowed down by 15.3% in very steep uphill sections for inclines exceeding 10%.

c. Influence of boundaries

Pedestrian behaviour on stairs is remarkably different than that on level surfaces. Schadschneider *et al*. (2009) noted that pedestrians like to put their hand on the handrail when negotiating stairs which is contrary to walking behaviour on flat surfaces where pedestrians usually try avoid walls or boundaries. In certain instances and operating environments, there is sometimes little possibility to use the handrails due to persons sitting on the stairs restricting such use.

Studies carried out by Pauls (1980) on data gathered by Hankin and Wright (1958), presented a linear relationship between flow rate (*q*) and width adopting a parameter called "*effective width*". This is the width after subtracting a boundary effect factor attributable to walls or hand-rails. Pauls' study adopts a width reduction of 150 mm from each side of a stair, but did however note that different circumstances could cause this width to be greater. Further detail in this regard is provided within the SFPE Handbook (Society of Fire

Protection Engineers *et al.* 1995), where a boundary effect width of 150 mm is given from a wall and 90 mm boundary effect width is given from the centre-line of a central handrail.

d. Influence of counter flow

Pushkarev and Zupan (1975b) observed a less than 10% capacity drop for a 75:25 bi-directional flow on staircases and up to a 14.5% capacity reduction for a 90:10 bi-directional flow. They also observed that bi-directional flow at space-densities of less than 0.93 m^2/pax (i.e. LOS C or worse) did not affect capacity.

Other than the work by Pushkarev and Zupan, very little has been researched into the relationship between counter-flow and capacity on stairs and is therefore an area worthy of further research.

e. Influence of stair geometry

Within the SFPE Handbook (Society of Fire Protection Engineers *et al.* 1995), the findings of observations conducted on four different riser and tread stair dimensions and how the capacity flow rates (q_c) are affected is tabulated in Table 2.7.

Table 2.7: The impact of stair geometry on flow rate (*q*); (Source: SFPE *et al.* 1995)

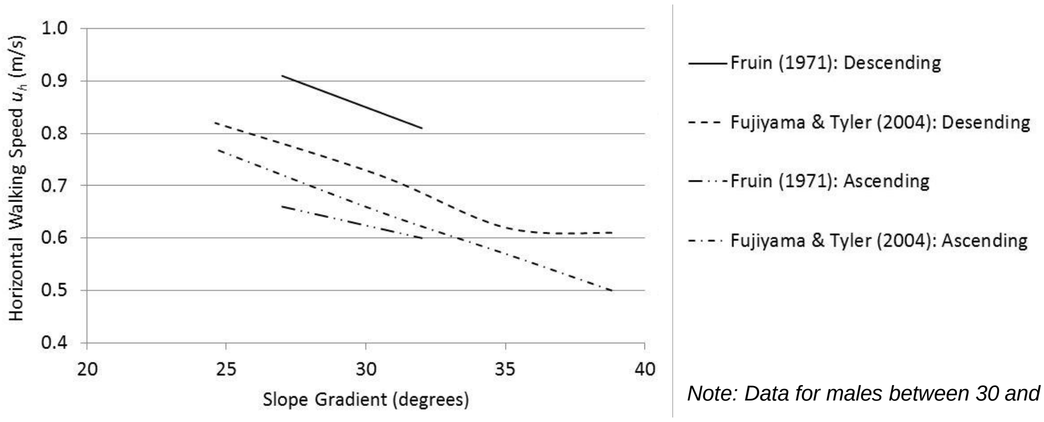
Observation (slope)	Riser (mm)	Tread (mm)	Flow Rate q_c (pax/m/min)
Stair 1 (37.0^o)	191	254	56
Stair 2 (32.5^o)	178	279	61
Stair 3 (28.5^o)	165	305	65
Stair 4 (26.5^o)	165	330	70

Reducing the stair gradient from 37^o degrees down to 26.5^o clearly shows an associated increase in stair capacity. This is consistent with the findings of Pauls (Society of Fire Protection Engineers *et al.* 1995) who listed a qualitative[43] performance standard for varying stair geometries as tabulated in Table 2.8.

Table 2.8: Stair performance in relation to gradient; (Source: SFPE *et al.* 1995)

Observation (slope)	Rise (m)	Tread (m)	Slope (degrees)	Performance
Stair 1 (26.5^o)	0.165	0.33	27	Highest
Stair 2 (32.7^o)	0.18	0.28	33	Medium
Stair 3 (36.7^o)	0.19	0.255	37	Lowest

Figure 2.14 shows the horizontal speed vs. slope gradient relationship comparison between work done by Fruin (1971a) and Fujiyama and Tyler (2004) for various stair gradients. The figure shows that, for both ascending and descending stair movements, average horizontal speeds for both datasets decrease linearly for increasing stair gradients. Note that Fujiyama and Tyler found the average descending speed to flatten past 35^{o} at around 0.61 m/s.



Note: Data for males between 30 and 50 years of age only.

Figure 2.14: The influence of stair gradient on horizontal walking speed (u_h)

2.4 Other Factors Affecting the Pedestrian Movement Dynamic

It is well known that other situational factors, such as culture, demographic characteristics, group size and level of mobility also play a role in human movement dynamics (Boles 1981; Knoblauch *et al.* 1996; Hoogendoorn and Bovy 2003; Willis *et al.* 2004). Whilst there are more factors found in the literature that affect human walking dynamics, this section highlights some of the more important factors affecting pedestrian movement.

2.4.1 Impact of Cultural and Ethnic Differences

The effect of culture is acknowledged in literature to have a key role in the size of personal space (Kaup *et al.* 2007) and hence affects the fundamental pedestrian flow relationships and MFD's. From the literature review conducted in this study, most pedestrian studies have been performed in North American, European and Asian countries with no evidence of any significant study done on the African continent.

According to Tanaboriboon *et al.* (1986), walking behaviour in Northern America and Europe appears to be similar, whereas walking behaviour in the Asian countries is significantly different caused by a different pedestrian size (Asian pedestrians are much smaller than in western countries) and culture (Asian pedestrians maintain smaller inter-pedestrian distances). Knutton (2004), Tanaboriboon *et al.* (1986) and Lam and Cheung (2000) also noted that Asian people tend to be more tolerant of heavy crowding (including the intensity of crowding) than their European counterparts. They also argue that more data collection is required for a larger range of flow conditions as no single fundamental flow model fits all pedestrian facilities supporting the fact that pedestrian flow characteristics are site- and region-specific.

This is acknowledged by Henson (2000) who states that cultural and ethnic attitudes towards walking should be considered in estimating acceptable LOS standards. Acceptance of different crowding conditions by different cultures was confirmed in a study by Saif (2009), who showed that Eastern and Middle Eastern societies accepted closer inter-person spacings and so argued that the HCM LOS standards (TRB 2000) are not applicable.

In a comparative study of general behavioural differences between various cultures/countries, Hofstede (1991), well known for his work on the four dimensions of cultural variability commonly referred to as "*Hofstedes dimensions*"[29], showed that South Africans scored high for masculinism and individualism, the dominant indicators for "*aggressive*" driving behaviour. The author believes that this aggressiveness may manifest in more aggressive pedestrian walking behaviour as well.

In another study by Trompenaars and Hampden-Turner (1998), eight cultural groups within South Africa were analysed and the study concluded that behavioural differences between these groups were significantly large when compared to behaviour observed in Europe and the USA. Since South Africa has a rich multi-cultural heritage originating from Africa, Europe and Asia, it is therefore considered incorrect to associate the pedestrian behaviour of another country with that of South Africa.

Finally, according to Matzopoulos *et al.* (2004), the fact that South Africa has a notorious history of violence is believed to contribute to a culture which appears to condone hostility, which may uniquely impact on the day to day and inter-gender pedestrian behaviour in public places in this country. This viewpoint is supported by Ronald (2008) who identified South African citizens as inherently aggressive people who have been desensitised to violence and aggressive behaviour. Ronald believes that "*it is this culture, together with other factors, that contribute to the lack of consideration for fellow human beings*" which, from personal observation, is apparent on Public Transport systems in South Africa, particularly rail.

2.4.2 Type of Facility and Trip Purpose

Walking speeds vary according to the type of facility studied. For example, people seem to walk faster when crossing roads than when on a footway (Knoblauch *et al.* 1996; Fugger *et al.* 2000). It is also likely that differences in walking speeds are a function of a pedestrian trip purpose (for example, shopping, leisure, business, transport interchange, school route) which proves significant because of the different goals and priorities of the pedestrians involved. As an example, Finnis and Walton (2007) found that people walking to and from the train station walk at a significantly faster pace than others. Surti and Burke (1971) found the average free-flow walking speed of tourists outside the Whitehouse in Washington to be 1.0 m/s while that of other pedestrians was 1.6 m/s.

Daamen (2004) reports pedestrians travelling for business purposes have the highest walking speed (1.45 to 1.61 m/s), followed by commuters (1.34 to 1.49 m/s), shoppers (1.04 to 1.16 m/s) and pedestrians walking for leisure purposes (0.99 -1.10 m/s). O'Flaherty and Parkinson (1972) found that pedestrian flows with different travel purposes have variation in walking speeds of up to 0.5 to 1.0 m/s. Free-flow walking speed for commuters of 1.5 m/s and 1.75 m/s for students has been observed by Roddin (1981).

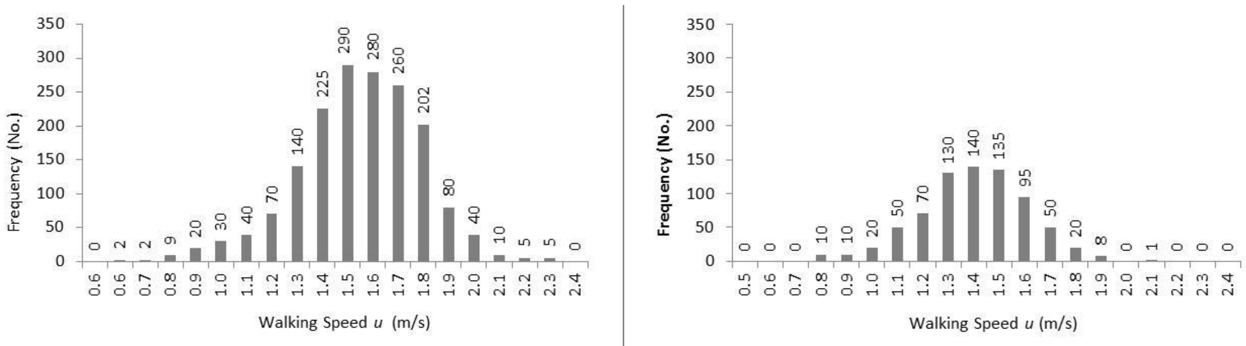
Penn and Turner (2001) believe that between 50 to 80% of the variance in pedestrian flows for different locations can be attributed to variations in configurational properties, viz. the make-up of the pedestrian infrastructure network.

According to De Langen and Tembele (2001) and Tregenza (1976), another important factor affecting walking speeds is the condition of the pavement, where harder surfaces have been reported to promote faster walking speeds than softer carpeted surfaces. De Langen and Tembele found that a pavement in a poor condition can reduce walking speeds by approximately 0.7 m/s and very bad pavements can reduce walking speeds by as much as 1.0 m/s.

2.4.3 Impact of Pedestrian Groups

Kretz *et al.* (2008) conducted empirical observations at the world exhibition in Hannover, Germany in 2000 and found that the observed walking speeds followed a normal distribution. They also looked at group size for groups of up to six people and studied the impact that group size has on the walking speeds. Their results revealed a drop in average walking speed ($\bar{u}$) from 1.38 m/s to 1.10 m/s for group sizes ranging from one person to six persons in a group respectively, a difference of 20.29%.

A recent observational study of free-flow sidewalk speed by Willis *et al.* (2004) of 2,613 pedestrians at three different locations in Edinburgh and York (United Kingdom) revealed that groups (i.e. groups of two or more people) had lower average speeds ($\bar{u}$ = 1.36 m/s) than individual pedestrians ($\bar{u}$ = 1.52 m/s), a difference of 10.52%. The histogram of the resulting speed distribution is shown in Figure 2.16 for single individuals (*a.*) and for groups of two or more persons (*b.*).



(a.) Single persons

(b.) Groups of two or more persons

Figure 2.16: Effect of group size on walking speed (*n* = 2,613); (Source: Willis *et al.* 2004)

From Figure 2.16, both datasets can be observed to be normally distributed, but for groups, it is shifted towards lower speeds compared with the distribution for single pedestrians. The findings of Willis *et al.* (2004) thus corroborate with the earlier findings of Knoblauch *et al.* (1996) who observed significant differences between the walking speeds of pedestrians walking alone and those walking in groups. This finding was later also observed by Kretz *et al.* (2008). Willis *et al.* also discovered that pedestrians talking to others and carrying baggage were found to have significantly slower speeds than pedestrians not talking nor carrying baggage respectively.

2.4.4 Effect of Encumbrances

The effect of encumbrances, in terms of carrying luggage or encumbered with children or with a physical disability on walking speeds is discussed in this subsection.

According to independent findings by Fruin (1971a); Whyte (1988) and Young (1998), there is no significant difference in walking speed between pedestrians carrying and not-carrying baggage. Research conducted on airport passengers in three Canadian airports by Davis and Braaksma (1988) revealed that "*encumbrances of luggage does not substantially affect free-flow speeds*" which coincides with the findings of Fruin, Whyte and Young.

This observation is however contrary to the findings of Knoblauch *et al.* (1996) where they found that pedestrians talking to others and carrying baggage were found to have significantly slower walking speeds than pedestrians without baggage.

A recent observational study of free-flow sidewalk speed (u_f) by Willis *et al.* (2004) of 2,613 pedestrians in Edinburgh and York (United Kingdom) revealed that the range of free-flow walking speeds ranged from 1.50 m/s for unencumbered pedestrians to 0.98 m/s for pedestrians with mobility aids (refer to Figure 2.16). Excluding mobility aids from the sample, the speed difference range between unencumbered and carrying shopping bags is still statistically significant (using ANOVA) and is in the order of 0.1 m/s.

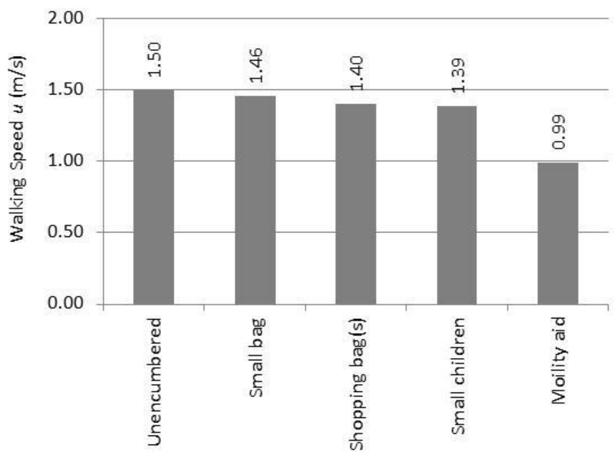
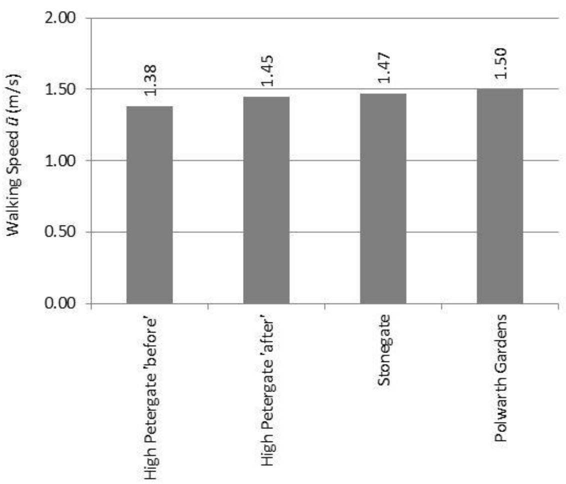


Figure 2.16: Effect of encumbrances on walking speed; (Source: Willis *et al.* 2004)

Whilst the findings of Willis's *et al.* agree with the findings of Knoblauch *et al.* (1996), they do not corroborate with the earlier findings by Fruin; Whyte; Davis and Braaksma and Young who stated that average walking speeds are not influenced by carrying a bag/luggage. However, it is important to note that the size and weight of the baggage is not defined and in this instance, could be too light to be considered a burden sufficient to slow walking speeds.

2.4.5 Effect of Location

Willis *et al.* (2004) also found that the range of average free-flow sidewalk walking speeds varied considerably between the case study locations (refer to Figure 2.17).



Note:
"before" refers to a scenario before traffic restrictions were put in place.

"after" refers to a scenario after traffic restrictions were put in place.

Figure 2.17: Effect of Location on walking speed; (Source: Willis *et al.* 2004)

The initial conclusion of their study was that the environmental context as a whole appeared to play an important part of pedestrian walking behaviour. However, when the "*groups*" and "*individuals*" were isolated for the dataset and assessed separately, it was found that the average walking speeds for individuals were "*remarkably stable across all locations*". The same is not true for groups of people, where significant differences in mean walking speed ($\bar{u}$) across locations was found.

2.5 The Concept of Level-of-Service and Quality-of-Service

Before any pedestrian spatial requirement can be determined (whether it be in railway stations or anywhere else), it is important to define how the evaluation criteria are currently defined and to review what past research has been conducted in this field, particularly with regard to the level-of-service (LOS) concept and whether the more recent quality-of-service (QOS) concept is perhaps more applicable in the assessment of pedestrian space.

2.5.1 Introduction

Estimation of pedestrian LOS is the most common approach used in assessing the quality of operations of pedestrian facilities. The importance of the appropriate choice of level-of-service for a particular facility represents a compromise between the high cost of providing extra space (for a good LOS) and the amount of inconvenience to pedestrians (at a poor LOS).

Fruin first introduced the concept of pedestrian level-of-service (LOS) in 1971 in an attempt to provide a scale to benchmark pedestrian activity using density and flow rate (Fruin 1971b). The scale proposed by Fruin makes reference to six grades, from a LOS A (unimpeded free-flow) to a LOS E (very restricted walking possible). A LOS F is not specifically defined in the table but is normally defined for conditions worse than LOS E where flow reduces to zero and walking is no longer possible.

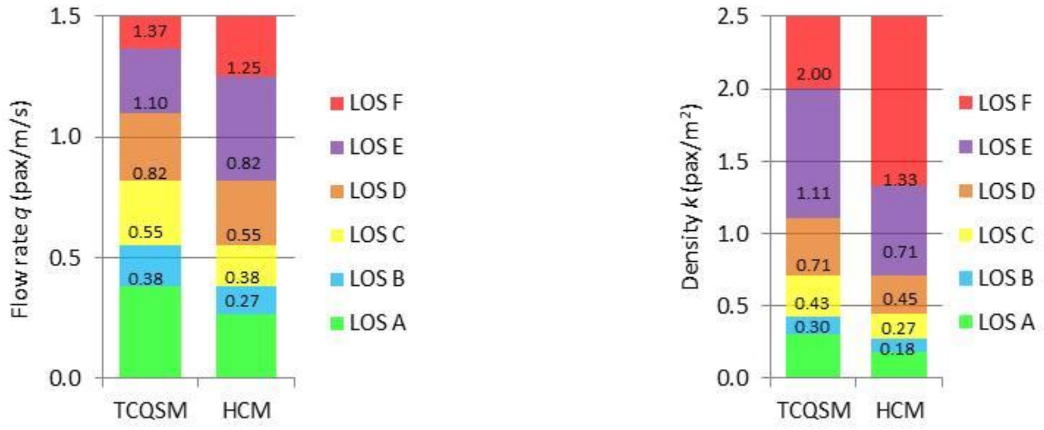
It must however be recognised that Fruin's measurements are based on pedestrian street environments and not in railway station environments where lower LOS can be expected to be tolerated for short durations. A comparison of the HCM LOS boundary values (TRB 2000), adopted from Fruin and the TCQSM LOS boundary values (TRB 1999c), adopted specifically for public transport facilities, is indicated for stairs in Figure 2.18 and in Figure 2.19 for walkways. From the graphs, it is evident that the TCQSM boundary values allow for greater flow boundaries, especially for walkways; see Figure 2.19 (*a.*) for flow rate LOS boundaries and Figure 2.19 (*b.*) for density LOS boundaries.

For walkways, the range of the LOS bandwidths (from LOS B to LOS E) essentially remains similar achieved by increasing the LOS A bandwidth in the TCQSM guideline. For stairs, the LOS A bandwidth remains similar, but the flow rate range of the LOS B and C bandwidths (see Fig 2.19 (*a.*)) boundaries have been increased in the TCQSM guideline. For the stair density LOS bandwidths (see Fig 2.19 (*b.*)), the LOS D bandwidth has been reduced in the TCQSM guideline in favour of a wider range bandwidth for LOS E.

According to Still (2000) and Pheasant (2002), Fruin's selection of body size data seems to be over-generous in terms of body size and clothing viz. attired in thick clothing more suited to very cold temperatures not applicable to warmer environments. The Fruin LOS guidance, which has been adopted by the HCM guideline document (TRB 2000) is also unfortunately applicable for uni-directional movement only and does not take into account bi-directional or cross-flow movement (Rouphail *et al.* 1998; Blue and Adler 2000).

(a.) Flow rate (q) LOS bandwidths   *(b.) Density (k) LOS bandwidths*

Figure 2.18: LOS boundary differences between HCM and TCQSM guidelines for stairs



(a.) Flow rate (q) LOS bandwidths *(b.) Density (k) LOS bandwidths*

Figure 2:20: LOS boundary differences between HCM and TCQSM guidelines for walkways

A method is however still needed to include these factors into the direct computation of LOS. Another aspect not taken into consideration in the determination of LOS, is crowd "*self-organisation*", which permit crowds to move at higher densities which, according to Fruin's definition, movement would be considered "*virtually impossible*".

2.5.2 Past Research on Level-of-Service

Recent research on pedestrian LOS indicates that there are a number of factors that affect pedestrians LOS. For example, both Naderi (2003) and Zhang (2004) are critical of the LOS tool employed by engineers since they argue that this concept was initially introduced for vehicles which therefore ignores the relevance of human factors and is therefore an oversimplification of the sensuous nature of the human being. Zhang (2004) prefers the notion of a gradual LOS transition "*which correlates better with human perception of LOS*" instead of rigid boundaries. A further criticism raised by Mateo-Babiano (2003) is that the Fruin LOS concept uses only two measures of effectiveness to evaluate pedestrian facilities viz. density and speed, which although simple and easily utilised, is not "*considered adequate and may compromise other more important factors*." Khisty (1994) and Henson (2000) both argue that there are additional environmental measures affecting perceived LOS including comfort, convenience, safety and security factors.

Although the research identifies various factors affecting pedestrian LOS, many of the factors are not included in the current computation of LOS. In order to address this complication, several researchers have proposed various alternatives to LOS discussed further below:

Mozer (1994) introduced a "*stress level*" concept of determining LOS levels based on a scale ranging from one to five. The higher the stress level, the lower the service level. The equation proposed by Mozer is however only applicable to sidewalks and incorporates pedestrian user types, traffic volumes, sidewalk widths, distance to roadway, one-way or bi-directional pedestrian volumes etc.

Towards a more inclusive LOS assessment scale, Sarkar (1995) and later Tolley (2003) introduced a qualitative evaluation method incorporating aspects such as safety, security, comfort and convenience, continuity, system coherence, and attractiveness. This research process led to the definition of "*overall LOS"* which proposed a method to combine the factors together to more appropriately indicate the overall value for the pedestrian LOS. According to Sarkar (1995), using the "*overall LOS*" criteria, people can better understand how well a particular street accommodates pedestrian travel. The *Highway Capacity Manual* (TRB 2000) provides a list of factors affecting pedestrian facilities, but offers little guidance on the contribution of each factor into a measure of overall LOS. Itami (2002) later referred to the "*overall LOS*" more appropriately as "*quality-of-service*", abbreviated as QOS.

Stonor, Beatriz de Arruda Campos and Smith (2003) introduced a "*Walkability Index*" for Transport for London (TfL) specifically to improve the walking environment and included criteria such as footway quality, width, gradients etc.

Both Henson (2000) and Correia and Wirasinghe (2006) supported the QOS concept but suggested that QOS should not just be based on spatial considerations but incorporate time delay as well. This concept, first introduced by Benz (1986), is referred to as the space-time (*ST*) concept and suggested that it could be calculated as a product of the number of pedestrians (*P*) involved in the activity, space-density required per person (m^2/pax) for the activity (*M*) and the time required, in seconds, for the activity (*T*). The Benz equation, as it is known, can be written as:

$$ST = P.M.T$$

.

The Benz equation allows for equivalent *ST* values for different values of *M* and *T* for an equal amount of pedestrians (*P*). For example, it is possible to have equivalent *ST* values between two scenarios where, in the first scenario, a LOS E activity lasts for one minute and in the second scenario, a LOS D condition lasts for say five minutes.

As already mentioned in Subsection 2.5.1, the major shortcoming of the existing standard pedestrian LOS methodology is that it does not adequately address bi-directional pedestrian flows which, according to Blue and Adler (2000) should be a factor introduced into the new QOS concept. Mozer (1994) attempted to address this by recommending the inclusion of a "*travel pattern factor*" (TPF) representing the one-way or bi-directional nature of a facility's pedestrian traffic.

2.5.3 The Impact of Culture on LOS

The impact of culture on pedestrian behaviour and on the macroscopic fundamental diagram (MFD) has already been discussed in Subsection 2.4.1. An example of the cultural effect of populations on personal space is acknowledged by Kaup *et al.* (2007) who argue that the Japanese population prefer a larger surrounding space than Americans, whilst Italians are able to tolerate smaller spaces. The acceptance of smaller inter-person spaces contributes to permitting higher capacity flow rates for the same density LOS standard. The importance of this is that infrastructure designs need not be as generous for the same flow rate for one population when compared to another population with a different culture.

In certain circumstances observed at the Royal Ascot racecourse (United Kingdom), persons were found to automatically keep their distance from each other despite high crowd densities (Brocklehurst *et al.* 2003). According to Brocklehurst, this is attributable to the fact that the population group sampled may be considered slightly more esteemed and therefore culturally different from the overall population.

Zhang (2004) raised a further important criticism of the LOS concept stating that the current "*LOS criteria ignores behavioural justification*". This essentially means that a moderate LOS prevalent in one country (possibly a developing country) could be perceived to be a poor LOS in another (possibly first world) country. This was indeed confirmed by studies conducted in the Middle East by Saif (2009) were it was found that the Middle Eastern population tended to accept more congestion for the same perceived LOS than Europeans.

A stated preference study undertaken by Lee and Lam (2003) in Mongkok Station, Hong Kong revealed that the proposed LOS standards (proposed by interviewees) were perceived to be identical to the Fruin LOS standard except for LOS A and B. This meant that the people in Hong Kong perceived a LOS A for higher densities than Fruin proposed before entering into a LOS B category. This is probably due to the smaller Chinese physique and willingness of Chinese to accept closer densities without feeling uncomfortable as proposed earlier by Tanaboriboon *et al.* (1986).

Pauls (2004) and Kaup *et al.* (2007) further mention that acceptance of actual physical contact varies between cultural population groups. Physical contact was identified by Trompenaars and Hampden-Turner (2004) as one of the elements contributing to a culture ethic amongst the other 11 influencing elements such as work ethic, public emotion, pace of life, noise, climate, literature, dress, music, architecture, food and language.

It is the experience of the author, as a result of the many observations undertaken at local stations, that South African public transport users (particularly rail users) are familiar with crowding effects and physical contact on a daily basis. It is however likely that this is not their preferred situation, but that, as a result of exposure to such poor levels-of-service over a long period of time, are willing to settle for closer inter-person distances (i.e. higher person densities) than their European or even Asian public transport counterparts for the same perceived LOS category. This is the same argument Tanaboriboon *et al.* (1986) made with Asian (Chinese) people mentioned earlier in this subsection.

2.5.4 LOS and QOS Relationship

Based on the discussion presented in the preceding subsections, there is a need to identify quality-of-service (QOS) incorporating additional factors within the LOS definition. This is necessary as occasionally, a low pedestrian count for a particular space would yield a good LOS standard when in fact there is a great demand for that space but it is not utilised due to other environmental factors e.g. poor lighting, security etc. Another example provided by Henson (2000) is when true demand may be diverted when pedestrians avoid already congested areas and use slightly more distant, but less utilised routes instead.

Whilst there is currently no established approach for the measure of QOS, an attempt to address a means to measure quality in the walking environment was proposed by Landis *et al.* (2000). Their proposed new LOS model incorporated statistically significant roadway and traffic variables that described pedestrians' perception of safety or comfort on sidewalks between roadway intersections. Some of the variables incorporated in their model included presence of a sidewalk, lateral separation from vehicles, barriers and buffer space, vehicular volume and speed etc. The model is similar in approach to the methods used to assess vehicular levels-of-service as recommended in the *Highway Capacity Manual* (TRB 2000).

Muraleetharan and Hagiwara (2006) conducted conjoint analysis[11] to evaluate pedestrian LOS in the city of Sapporo, Japan. Conjoint analysis estimates an individual's "*value system*" and identifies how much value a user associates to each of the attributes. Their study provided insight into which factors contributed to poorer or better LOS and their results indicate that whilst the total utility value has a linear relationship with overall LOS, that the slope of the line may be different for individual countries or cultures as shown in Figure 2.20.

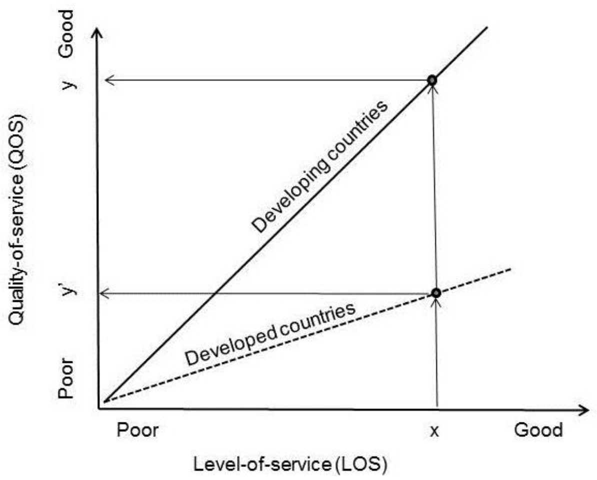


Figure 2.20: Relationship difference between LOS and QOS for developed vs. developing countries

By way of explanation, for a particular scenario operating at LOS = *x*, the developing countries might perceive this to be acceptable conditions (viz. at QOS = *y*) whilst the developed countries may associate this QOS as totally unacceptable (viz. at QOS = *y'*). The relationship between QOS and LOS is however not well established and further research into this field is still required.

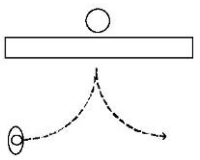
2.6 Boarding and Alighting Pedestrian Dynamic

Part of the boarding and alighting dynamic occurring at stations involves queuing on platforms and so in this section, various types of queuing behaviour observed in practice are defined. In large public spaces, different kinds of pedestrian queuing behaviour are evident and in many cases queue spaces are also circulation spaces i.e. whilst some pedestrians form queues, others pass through these queue spaces. Even in forming a queue, several steps of movement are observed, viz. approaching queues, standing in queues, moving forward, getting serviced, and getting out of queues.

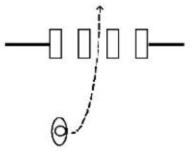
2.6.1 Queuing Types

On the basis of the observation of the movement of pedestrians in airports, railway stations, department stores, and office buildings, Okazaki and Matsushita (1993) classified three types of queuing behaviour viz. Types 1, 2 and 3 shown in Figure 2.21 (*a.*). Type 3 can be further classified into two sub-types (viz. Type 3-1 and Type 3-2) shown in Figure 2.21 (*b.*).

A similar classification system is proposed by Dewei and Baoming (2006). They classify three types of queues for Mass Transit Railway facilities, viz. Types A, B and C equivalent to Okazaki and Matsushita's Type 1, 2 and 3 classification. Type A refers to the linear queuing at a typical ticket kiosk; Type B refers to competitive queuing at turnstiles and Type C is the typical lift or train door queue behaviour. In this study, the Okazaki and Matsushita queuing classification will be used.



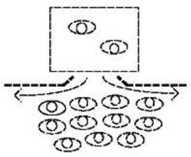
<u>Type 1</u> :
Pedestrians form linear queues in front of a counter. Pedestrians approach the queue, stand in the queue, move forward, get serviced, and get out of the queue. This type of movement can be seen at the reception counters in stations, department stores, hotels, banks, and so on.



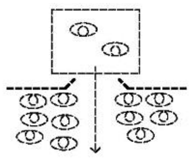
<u>Type 2</u> :
Pedestrians form queues in front of gates and pass through after they get serviced. This type of movement can be seen at the turnstiles in railway stations, entrances of theatres, museums, and so on.

<u>Type 3</u>: Pedestrians form queues in front of the doors of coaches. When a coach arrives, boarding pedestrians wait for the on-board passengers to alight before boarding themselves. This type of movement can be seen at elevator halls, platforms of railway stations, bus stops, and so on.

(a.) Classification of Types 1, 2 and 3 queuing behaviour



<u>Type 3-1</u>:
Pedestrians gather in front of the entrance without leaving the way for on-board passengers to get off the vehicle.



<u>Type 3-2</u>:
Pedestrians leave the way for on-board passengers to get off the vehicle.

b.) Classification of Types 3-1 and 3-2 queuing behaviour

Figure 2.21: Types of movement in queue spaces; (Source: Okazaki & Matsushita 1993)

2.6.2 Train Dwell Times

In the USA and Canada, the proportion of dwell time[16] productively used for passenger movements ranges from 31 to 64% of the total dwell time (TRB 1999b). Dwell times for 1,662 observations over ten stations in the USA and Canada revealed an average train dwell time of 39.0 sec. The range of dwell times is shown in Figure 2.22 below (Values shown indicate the average dwell time (D_t) and bar lengths represent the extents of the standard deviations):

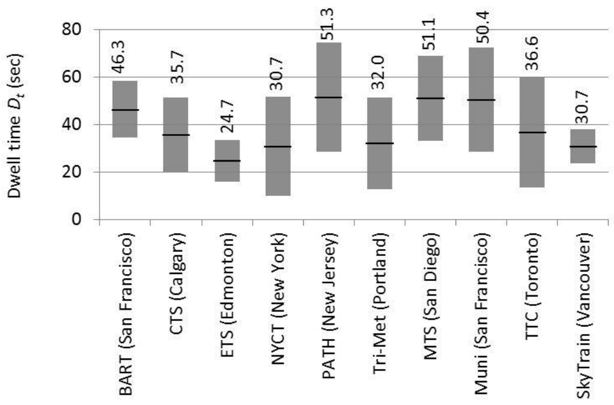


Figure 2.22: Train Dwell times in Canada and USA; (Source: TRB 1999b)

Studies by Puong (2000) on the results of observations at seven MBTA stations in Boston (USA), revealed that dwell times are a linear function of passenger boarding and alighting times and a non-linear function of the on-board coach crowding level.

2.6.3 Boarding and Alighting Rates

The study of boarding and alighting (B&A) rates is considered important particularly since the results of studies by Zhang, Han and Li (2008) revealed that pedestrian B&A behaviour varied from country to country because of the diversity of characteristics, service levels and other factors.

Observed passenger boarding and alighting rates for various stations in the USA and Canada represented in terms of time per passenger per single stream (in seconds), as documented in the TCQSM manual (TRB 1999b) are shown in Figure 2.23.

In the figure, green bars represent mixed boarding and alighting flow, red bars represent boarding flows only and blue bars represent alighting flows only. Table 2.9 tabulates average passenger boarding and alighting rates from the figure and differentiates between doors that have steps with those that do not. It can be deduced that steps have a marked impact on the boarding and alighting rates, taking approximately twice as long to board or alight when compared directly to the sample set without steps.

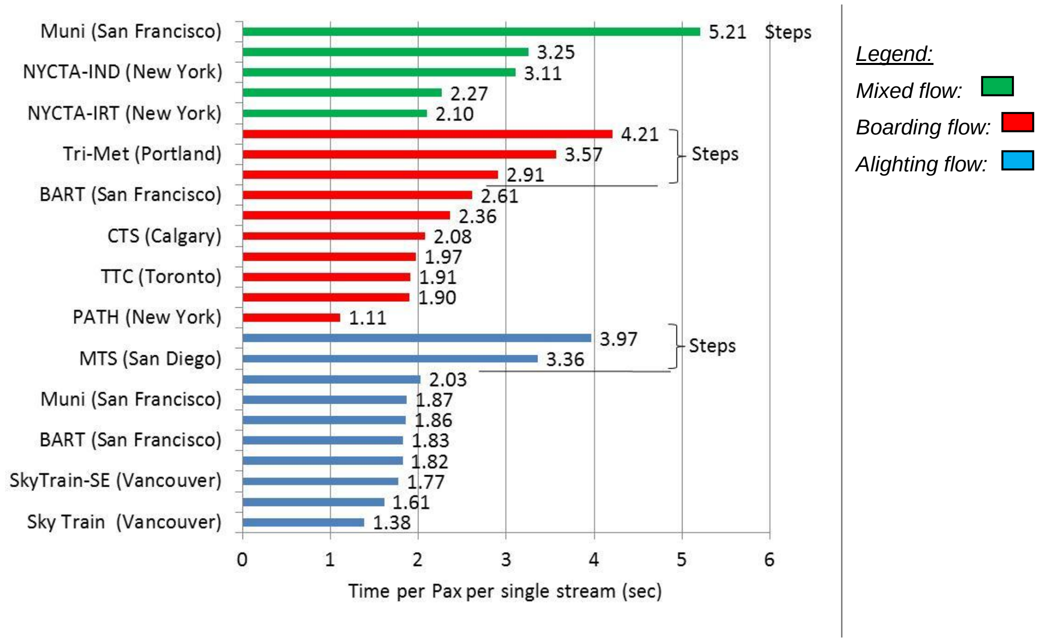


Figure 2.23: Boarding and alighting rates observed in Canada and USA; (Source: TCQSM 1999b)

Note that door widths have not been identified in the observations, but the same document reports that "*door widths on observed systems seemed to have little effect on flow rates*" (TRB 1999b:5-23).

Table 2.9: Average boarding & alighting rates observed at Canadian and American stations; (Source: TRB 1999b)

Movement	Steps only	No Steps
Alighting	3.67 sec/pax	1.77 sec/pax
Boarding	3.56 sec/pax	2.11 sec/pax
Boarding and Alighting	5.21 sec/pax	2.68 sec/pax

Daamen and Hoogendoorn (2003a) conducted B&A observations at 11 Dutch stations and observed mean boarding and alighting times of around one second per passenger in clusters and found that this time was dependant on the width of the door opening. Differences of +10% and -10% were observed in the mean B&A times for narrower versus wider train doors respectively, thus disputing the earlier TRB (1999b) comment regarding the insensitivity of flow rates to door widths. Harris and Anderson (2006) compared survey results of 30 stations around the world and observed that passenger boarding rates varied between 0.37 and 1.58 pax/m/s and alighting rates ranged between 0.18 pax/m/s and 1.77 pax/m/s. The ranges are attributable to the varied types of platform height differences, door widths, directional flows (i.e. ether boarding, alighting or both) etc. Of importance to this study is that they also postulated that culture plays an important role in B&A behaviour, but this was not explicitly researched.

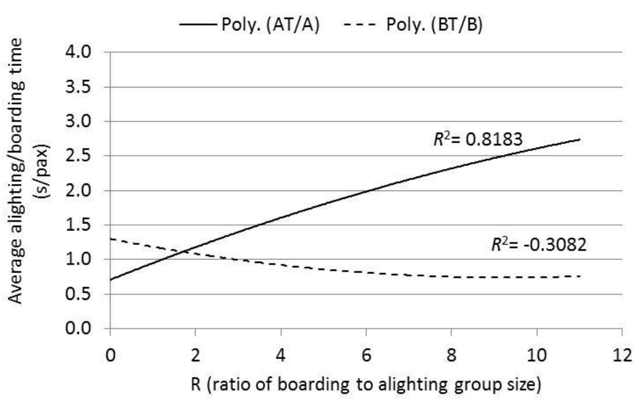
Daamen, Lee and Wiggenraad (2008) conducted B&A experiments in a controlled environment and found that increasing the horizontal and vertical door clearance between the platform level and edge respectively resulted in up to a 15% decrease in doorway flow capacity. The results of their experiments are indicated in Table 2.10.

Table 2.10: Boarding & alighting capacities (sec/pax) for 80 cm door widths; (Source: Daamen *et al.* 2008)

Vertical Gap (cm)	Horizontal Gap (cm)					
	No Luggage			Luggage		
	5	15	30	5	15	30
5	1.10	-	1.18	1.45	-	1.37
20	-	1.12	1.14	-	1.61	1.56
40	1.23	-	1.30	1.54	-	1.59
60	-	1.19	1.30	-	1.67	1.79

They found a 25% decrease in doorway flow capacities when passengers carried luggage (suitcases), although size of the suitcases was not defined. A criticism of their study, however, is that they required the platforms and coaches to be fabricated in the laboratory with platforms built to only a 2.5 m width, considered by the author to be too narrow to mimic a real-life scenario. Their experiments incorporated a constant door width of 0.8 m. From the table, observed passenger boarding and alighting rates varied between 0.96 pax/m/s (1.30 sec/pax) and 1.14 pax/m/s (1.10 sec/pax) for no luggage and ranged between 0.70 pax/m/s (1.79 sec/pax) and 0.91 pax/m/s (1.37 sec/pax) for luggage-laden passengers.

Zhang *et al.* (2008) conducted B&A observations at three stations in Beijing, China and found that boarding and alighting occurred simultaneously rather than sequentially. A linear relationship between B&A time per person and *R* (ratio of boarding to alighting group size)[4] was observed, rather than a standard average B&A rate. Figure 2.24 illustrates the relationship.



Legend:

A: number of alighting passengers (alighting group size)

AT: alighting time in total (s)

B: number of boarding passengers (boarding group size)

BT: boarding time in total (s)

AT/A: average alighting time (alighting time per person)

BT/B: average boarding time (boarding time per person)

R: the ratio of B over A (B/A)

T: alighting and boarding time in total

H: time of simultaneous alighting and boarding (time in interweavement)

Figure 2.24: Average alighting / boarding time vs. *R* ; (Source: Zhang *et al.* 2008)

Some interesting results are presented by Zhang *et al.* As shown in Figure 2.25, average alighting time (alighting time per person) seems to get longer with the increasing values of *R*. This means that a high ratio of boarding to alighting group size leads to longer average alighting time. On the other hand, average boarding time tends to decrease with the increase of *R*, but the correlation coefficient is low. According to the regression analysis by Zhang *et al.*, average alighting rates ranged from approximately 0.8 to 2.7 sec/pax depending on the value of *R.* Similarly, boarding rates were found to be in the range of 0.7 to 1.4 sec/pax.

In October 2008, Fernández *et al.* (2010) conducted boarding and alighting experiments on buses in Santiago, Chile and found that average boarding rates were 1.74 sec/pax and alighting rates were 1.26 sec/pax for trunk route buses. Boarding rates of 2.08 sec/pax and alighting rates of 1.68 sec/pax were observed for feeder bus routes for pre-paid users. Interestingly, the same researchers conducted laboratory experiments and found that providing a vertical difference of 150 mm between platform and vehicle floor improved boarding and alighting times when compared to a zero level difference. This observation is contrary to the findings of Daamen *at al.* (2008).

3. EMPIRICAL PEDESTRIAN FLOW SURVEYS UNDERTAKEN AT STATIONS

In order to compare the international pedestrian flow results against those found in South African conditions, it was necessary to conduct detailed pedestrian observations at local railway stations.

Personal factors considered to influence walking speed include walking purpose, walking with children, shoe type, interacting with the environment etc. Adult pedestrians walking with young children, either by holding their hand, carrying them or pushing them in a pram, are expected to have slower walking speeds than pedestrians without children.

The chapter begins with an investigation into the various technologies available for pedestrian empirical data collection, together with a discussion on the selection criteria in determining the station sites and how privacy issues were overcome. A detailed account follows regarding the data collection phase of the research including measurement areas, data collection parameters and a discussion of the problems encountered during the survey process. The final section of the chapter deals with how the video observations were processed towards obtaining meaningful data.

3.1 Research Methodology

This section presents the methodologies considered for undertaking the empirical research and motivates which one of these has been selected and used in this study.

3.1.1 Introduction

For gaining insight into the development and calibration of the SP-model, a comprehensive desk research exercise was performed to gather information from both local and international literature. As presented in Chapter 2, this resulted in an overview of relevant existing empirical data, theories and pedestrian models in general and also identified the lack of local knowledge in this field. The research conducted in this study contributes to this local knowledge.

The primary empirical data collected in this study concerned pedestrian walking behaviour in general and pedestrian traffic flow characteristics in local railway stations in particular. It was not possible to isolate the influence of different factors on pedestrian walking behaviour, but surveys were conducted such that exogenous factors were constant or kept as uniform as possible (e.g. weather, time of day etc.). These primary observations were complemented by secondary observations which included boarding and alighting (B&A) data, train dwell times (D_t) and passenger arrival rates[41] (*PAR*).

3.1.2 Survey Methodology

The analysis of pedestrian movement is hampered by the difficulty of obtaining accurate data in a timely and cost effective manner that does not perturb the area being observed. Technological advances in computer and video processing over the last decade have significantly changed how pedestrian studies are conducted. A number of approaches are available to analysts but these all have their limitations. The most common techniques involve the use of a number of human observers counting the pedestrians and observing an area with a video camera and then analyzing the resulting videotapes. Both techniques are expensive because the former uses a lot of person resources to observe the space and the latter because it takes a long time to analyse videotape footage. Both techniques are prone to human error because observers cannot be expected to accurately record movements in a complex area and analyzing video footage is tiring, especially when the same piece of footage is reviewed several times to obtain all the information from it. In both cases, the resulting data has to be transformed into some form of readable electronic format in order to undertake the required analyses, which in itself is error prone. The effects of variation in the lighting or weather conditions of the area being observed are also added exogenous complications.

As the pedestrian data required is quantitative, the methodology required to obtain the information needs to be accurate and allow for a high sampling rate. During the course of the literature review, it soon became apparent that real-time data recording using some sort of video equipment would best meet the needs of the research. Visually counting the number of pedestrians for specific time intervals was considered too risky with no means of post-survey data verification.

Previous researchers (Bechtel 1970; Willis *et al.* 2002) also caution that video observations must be as unobtrusive as possible to avoid the well-known "*observer effect*" otherwise known as the "*Hawthorne effect*"[26] which may alter pedestrian behaviour because the subject person is aware of being observed.

Several researchers including Willis *et al.* 2002; Teknomo 2002; Hoogendoorn, Daamen and Bovy 2003; Osaragi 2004; Lee and Lam 2005 and Hostikka *et al.* 2007 have already successfully used video recording equipment to study walking speeds on stairs and on level ground including video recording of controlled evacuation behaviour in public buildings.

Since fully automatic path coordinate tracking is not reliable (Teknomo 2002), the semi-automatic pedestrian tracking process is the preferred data collection procedure used in this research. Semi-automatic tracking is not a new technique. Teknomo, Takeyama and Inamura (2001a); Teknomo (2002); Mauron (2002); Willis *et al.* (2002) have all developed and used semi-automatic tracking software to analyse pedestrian data.

3.1.3 Overall Research Methodology

An obvious shortcoming identified in the field of local pedestrian dynamics is the scarcity of empirical data. This research attempts to narrow this gap by collecting and analysing large amounts of empirical data observed and collected at two stations in Cape Town, South Africa. The data was used to calibrate the SP-model developed in this study.

A method to gather microscopic pedestrian flow data from video camera images was developed and discussed later in Section 3.3. The method of extracting microscopic (individual) and macroscopic (crowd) data from video recordings of real life pedestrian crowds, filmed at the two selected station locations, is also described.

At the beginning of the research programme (viz. in 2007 and 2008), the author visited a wide range of stations to obtain an understanding of the structure, functionality, control systems and architecture of existing railway stations. The reconnaissance of each station not only focused on the suitability for conducting observations, but also helped towards understanding the subtle variations in functional operation of each station. The stations visited are indicated in Table 3.1.

Table 3.1: Stations visited for preliminary observation purposes in Cape Town, South Africa

Cape Town main station	Khayelitsha station	Stock Road station	Maitland station
Mutual station	Mandalay station	Nonkqubela station	Eerste River station
Ysterplaat station	Salt River station	Lentegeur station	Koeberg station
Nolungile station	Bellville station	Phillipi station	Esplanade station
Woodstock station	Pinelands station	Langa station	Bonteheuwel station
Heideveld station	Athlone station		

Stock Road, Mandalay and Lentegeur stations proved to be the most appropriate stations in terms of universal access for special needs passengers[48] (SNP) provision, whilst it was found the other stations lacked this necessary functionality altogether. It was found that stations generally operate within (or have) five primary functional zones within which pedestrians function as indicated in Table 3.2.

Table 3.2: Station functional zones

Infrastructure type	Pedestrian Type	Zone	Function
Walkway (or Skywalk)	Non – commuter, shopper	Free	Street-to-street accessibility Retail activity
Foyer	Commuter	Free	TVP entry queuing
Ticket Verification Points (TVP's)	Commuter	Ticket verification	Access for paid customers only.
Concourse	Commuter	Paid side of TVP's	TVP exit queuing Distribution onto platforms
Stairs	Commuter	Stairs to platform	Platform access (Seating - unintentional)
Platforms	Commuter	Paid only	Waiting (inclu. seating) Boarding and Alighting zone

There are very few local stations that are equipped with lifts, and those provided are typically non-functional. The current policy within the rail authority is not to provide escalators and accordingly, no stations (apart from Cape Town station) have escalators. Both lifts and escalators are considered high maintenance items that the South African rail authority can ill afford and is hence the reason for exclusion of these items in Table 3.2.

The author was fortunate to visit several underground and National Rail stations in and around London, United Kingdom in November 2009, the metro stations of Lisbon, Portugal in July 2010, Tokyo metro stations in Japan during the month of October 2010 and several metro stations in Paris, France in November 2010. Most of the international rail stations visited, apart from the presence of escalators and lifts, complied with the same operational model defined in Table 3.2 above.

The preliminary study of the local stations listed in Table 3.1 formed the pool of potential survey sites for gathering empirical data. Due to the uncontrolled and complex nature of cross-flows at foyers and concourses, observations were not considered for this infrastructure type. Depending on the station layout, the stairways, skywalks and platforms were thus considered the only potential measurement areas for surveying pedestrian flow characteristics.

However, prior to selecting actual infrastructure measurement areas, it was considered important to identify appropriate station sites within Cape Town that could truly represent the cultural diversity of the South African society. It should be noted that studies undertaken at culturally diverse locations would however not accurately represent locations where such diversity is not present.

3.1.4 Rail Use Demographics in Cape Town

Population and demographic rail use characteristics for South Africa were obtained from the Census 2001 dataset (Central Statistic Services 2001). Table 3.3 shows the train user population per major metropolitan city in South Africa (values are rounded to the closest thousand persons).

Table 3.3: Rail use demographics in South Africa; (Source: Central Statistic Services 2001)

City	Black	Coloured	Asian/Indian	White	Total
Cape Town	96,000	88,000	1,000	11,000	196,000
Johannesburg	84,000	2,000	0	1,000	87,000
Pretoria	80,000	1 000	0	1,000	82,000
Durban	49,000	0	2,000	1,000	53,000
Total train users	310,000	91,000	3,000	14,000	41,000
Total train users (%)	49.1%	44.9%	0.6%	5.4%	100%
Total SA Population (%)	79.0%	8.9%	2.5%	9.6%	100%

From the table, Cape Town has more than double the train ridership than any other city in South Africa. Furthermore, Cape Town is the only city with such cultural diversity using trains, with almost a 50:50 train ridership for the black:coloured race groups. For the purposes of data collection, the selection of stations within the Cape Town metropolitan area was therefore considered to be a good representation of the South African demography.

For all commuters in Cape Town, walking and private car are the dominant travel modes with 33.5% and 33.8% of the mode share respectively. This is followed by train and minibus-taxi use with modal shares of 11.9% and 11.2% respectively. Table 3.4 tabulates the Cape Town rail patronage volumes segregated by gender and race group.

Table 3.4: Daily rail use in Cape Town segregated by gender & race group; (Source: Central Statistic Services 2001)					
Gender	**Black**	**Coloured**	**Asian/Indian**	**White**	**Total**
Male	54,000	46,000	600	5,500	106,100
Female	42,000	42,000	400	5,500	89,900
Total	96,000	88,000	1,000	11,000	196,000

From the table above, on average it is observed that there is a slightly higher train ridership for the male population viz. 54% compared to a 46% use by females in Cape Town. It is to be noted that the combined Black and Coloured population groups constitute 94% of the Cape Town rail users, which therefore became a factor towards selecting survey stations which serviced these two major population groups rather than making observations at stations which serviced the White or Asian community.

The reader is to note that whilst the data in Tables 3.3 and 3.4 is dated (i.e. over 10 years old), unfortunately no further census data has since been collected in South Africa to verify the patronage demographic split presented.

3.1.5 Data Collection Possibilities

The next decision to be made was deciding on the most appropriate technology for the collection and recording of the empirical pedestrian data with the aim of deriving macroscopic flow characteristics from these observations.

Firstly, data can be collected either from real-world observations or by conducting laboratory experiments that attempt to replicate the real-world environment. For real-world observations, the equipment and personnel are moved to the observation location, but the exogenous conditions and the pedestrian flows cannot be influenced. Despite the best preparation, the conditions and the pedestrian flows may always be (and sometimes are significantly) different than the expected situation. Also, influencing factors (such as temperature, weather, lighting etc.) cannot be separated, but combinations of these factors are observed.

Although laboratory experiments have been used effectively to collect empirical data (Daamen and Hoogendoorn 2003d), this has not been considered practical from a cost point of view and due to likely complications and difficulty in acquiring an acceptable (and diverse) sample of people that would best represent the public transport user. For example, respondents to a request for experimental participation may come from able bodied unemployed people, which may skew the results. Additionally, controlled environments would subject the participants to the well-known "*Hawthorne effect*" further contaminating the data since people are not walking in their natural environment, but in an artificial set-up. Furthermore, as the incentive of a participant is not directly related to the motivation of being in a railway station in the first place, their drive to hurry or stand (very) close to other pedestrians might be lower than in practice. This might lead to pedestrian walking behaviour with lower densities and lower speeds in relation to reality.

One of the objectives of identifying a suitable data collection method was to identify real-world observation techniques that offered to maximise the amount of information that could potentially be obtained for a given amount of effort. Table 3.5 provides a listing of the available techniques used worldwide.

Table 3.5: Data collection methods considered

Data Collection Method	**Advantages**	**Disadvantages**
Manual Counting (using hand held devices)	B&A data possible Pax flows possible Walking times can be determined	Difficult at high volumes/densities No possibility of data verification Cannot determine macroscopic relationships
GPS - devices	Allows for accurate tracking	Expensive/costly equipment Disturbs sample Not practical
Infrared- devices	Pax counting only	Limited range of application Cannot determine macroscopic relationships
Video recordings	Provides a visual data record Can determine macroscopic relationships Data verification possible	Privacy may be an issue Camera needs to be discrete/covert
Questionnaires/ Stalking	Route choice possible Determination of Individual speeds	Low sample rate Cannot determine macroscopic relationships

To date, data collection techniques involving pedestrian observations typically involve manual counting, GPS, infrared, video recordings and questionnaires and/or stalking. Table 3.5 shows manual counting as one of the techniques used for the observation of certain pedestrian processes in transfer stations (viz. boarding and alighting, passenger flows and walking times). In these instances, hand-held computers appear to be a useful tool, especially because their interface can be designed for each observation. Manual counting however, is not sufficient for analyses of macroscopic relationships between density, flow and speed and was therefore not considered in this study.

Theoretically, it is possible to continuously know the position, speed, and walking direction of pedestrians using GPS-receivers. However, this has a practical problem, as this equipment is not only costly, but also has to be handed to pedestrians while walking over an indicated area and has to be returned afterwards. The practicality, cost factor and the fact that GPS distribution would disturb the data collection process led to abandoning this method early in the evaluation process.

Infrared detectors are capable of counting passing pedestrians automatically and some can even derive trajectories every two seconds. The sensor monitors changes in ambient temperature which has the disadvantage that it cannot differentiate between pedestrians walking in a group. An experiment by Kerridge *et al.* (2004) tested the ability of the system to cope with large numbers of people moving in a simple space incorporating counter flows from an entrance to one side. They found that the current limitations of the equipment is that it cannot monitor more than eight people in the area being observed and is therefore only suitable to monitor LOS A type environments and was thus not considered suitable for application.

Data collection by means of video recordings thus remained the most promising data collection technique. One of the requirements for obtaining quality video data is that the recorder should be mounted directly above the walking area if possible, which makes it difficult (if not impossible) to be applied in most stations. Other requirements concern constant light conditions, a fixed location of the camera and continuous supervision of the camera and recorder. After the transformation of the video images into data (discussed later in Section 3.3), various data analyses may be performed.

A further advantage of video recording as a data collection mechanism is its ability to store the data, which can be reviewed to provide information on other aspects of the scene. Volume and speed data can be gathered separately at different times in the laboratory. Video recording provides an accurate and reliable means of recording pedestrian volumes, as well as other data, but requires time-consuming data reduction in the office as observed by Teknomo (2002). Unfortunately, the expense of reducing video data is very high because it must be done manually in the laboratory. A small survey on the availability and accuracy of automatic video analysis software for pedestrian detection was made but the results were unsatisfactory.

A few software companies claim that their system can detect pedestrians from the video images, however some of the systems only worked online with the installed surveillance cameras. One company tested their system on the video material recorded during a public library evacuation, but the results were not promising according to Hostikka *et al.* (2007). According to the company's own announcement, in order to reliably count people passing the virtual lines in the video image, the camera is required to be placed almost directly above the area being monitored, but in practical field tests, this is rarely possible.

Visio Pacs, a commercial system that automatically counts real-time passenger traffic in stations, is reported to be more than 97% accurate and has a rapid detection rate of 25 images per second (Fadin, Biasoli and Colmano 1997). The trajectory of a person is followed and on passing a central imaginary line, the person is counted in the direction corresponding to their trajectory. The system uses a video camera placed above the passageway aimed towards the floor. Detection is ensured by a wired neural network, which memorises floor texture when no one is in the passageway area.

A method for counting passenger streams was presented by Berrou *et al.* (2005) in December 2004 in collaboration with the New York City Transit Authority (NYCTA), where an extensive pedestrian measurement study involving n = 5,562 pedestrians at Grand Central Metro Station, New York was carried out. Here the pedestrian footpaths were tracked instead of head movements. This proved to be an accurate measuring system with less than 1% error recorded, but was found to be practical only for low density (LOS A) conditions.

Since route choice was not an area of interest or of significance in this study, the two techniques applicable in the identification of route choice, i.e. <u>questionnaires</u> and <u>stalking</u> were not considered.

3.1.6 Station Site Selection

For reasons identified in Subsection 3.1.4, station site selection for this study was restricted to the metropolitan area of Cape Town. Stations in the other three major city centres in South Africa viz. Johannesburg, Pretoria and Durban were not included in the research due to the budgetary and resource requirements as well as the great geographical distances separating these cities (in excess of 1600km).

Cape Town has the busiest train corridor in the country incorporating the Khayelitsha-Cape Town corridor (which includes the Kapteinsklip/Mitchells Plain section) with 338,000 daily passenger trips (SARCC 2006b), which is 27% higher than the second highest rail corridor, the Mabopane corridor in Pretoria. Furthermore, it is the only place in the country with an almost equal split between the coloured (44.9%) and black population (49.1%) race groups potentially providing a more diverse sample population than elsewhere in South Africa, depending on the station location.

The selection of stations in Cape Town for the purpose of undertaking pedestrian observations began with the development of a potential survey station list. For each station, the list was populated with station passenger volumes, whether or not they were concourse stations and suitability of the station layout for the erection of video cameras.

The top ten busiest stations in Cape Town according to SARCC *et al.* (2008a), were tabulated together with all the overhead concourse type stations as shown in Table 3.6. The listing on the left side of the table shows the ten busiest stations in Cape Town according to daily passenger volumes and the right side of the table shows the sixteen stations in Cape Town that have elevated concourse infrastructure. Concourse type stations were considered purely for the suitability of video camera vantage points over platforms and stairs.

Table 3.6: Busiest stations ranked according to pax volume & concourse infrastructure (Source: SARCC *et al.* 2008a)

No.	Busiest Stations	Daily Pax demand	No.	Concourse Stations
1	Cape Town	140,733	1	**Bonteheuwel**
2	Bellville	64,501	2	**Phillippi**
3	Mutual	54,981	3	**Khayelitsha**
4	**Bonteheuwel**	54,926	4	Koeberg
5	**Phillippi**	52,961	5	Lentegeur
6	**Salt River**	51,982	6	**Maitland**
7	Langa*	41,555	7	Mandalay
8	**Maitland**	36,324	8	Ndabeni
9	Nyanga	30.807	9	Netreg
10	**Khayelitsha**	29,991	10	Nolungile
Notes : *: *Under construction/upgrade at the time of assessment.*			11	Nonkquebela
			12	Nyanga
			13	Pinelands
			14	**Salt River**
			15	Woodstock
			16	Ysterplaat

From the two listings shown in the table above, five stations emerged as potential candidates (highlighted in the table) for the site observations viz. Bonteheuwel, Phillippi, Salt River, Maitland and Khayelitsha stations.

The next step towards the final station selection process involved a site visit to each of these stations to identify the appropriateness of the station and to confirm possible vantage points from which to erect video cameras to obtain the necessary video footage. As a result of a site visit, both Phillippi and Salt River stations were not further considered as platform shelters blocked the potential stair and platform measurement areas from the ideal video camera vantage point. Khayelitsha Station, whilst a viable possibility, was disregarded purely for the personal security concerns and geographical distance. Other stations such as Bellville, Ysterplaat, Koeberg, Mutual and Woodstock stations were visited separately and were also excluded for various reasons.

The site observations thus revealed that Bonteheuwel and Maitland Stations were most suitable for video observations with accessible overhead concourse facilities providing uninterrupted and safe vantage points over numerous measurement areas such as skywalks, platforms, staircases and trains themselves for the purposes of observing dwell times and B&A behaviour.

Bonteheuwel Station has an approximate 55,000 daily person trip volume with 20 and 27 scheduled train stops in the AM and PM peak hours respectively. Maitland Station has an approximate 36,000 daily person trip volume with a greater number of scheduled train stops in the peak hour as it serves the Cape Flats line as well. The busiest peak hours and corresponding passenger volumes are shown in Table 3.7.

Table 3.7: Maitland & Bonteheuwel station peak hour periods and passenger volumes

Time Period	Maitland Station		Bonteheuwel Station	
	Pax Vol.	Period	Pax Vol.	Period
AM Peak hour	7,472	06:38 – 07:38	14,486	06:30 – 07:30
PM Peak hour	6,275	16:50 – 17:50	8,704	16:47 – 17:47

Figure 3.1 shows the rolling 15-minute average boarding and alighting volumes at the two selected stations. From the figure, the AM and PM peaking phenomenon is evident with greater activity occurring at Bonteheuwel Station in the morning peak period. Both stations are relatively quiet during the inter-peak time period from 09:00 to 15:00.

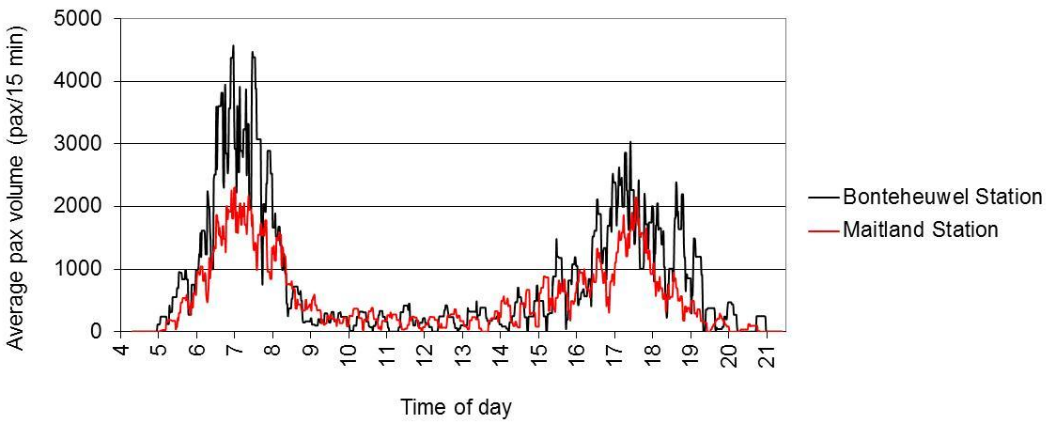


Figure 3.1: Bonteheuwel & Maitland rolling 15-min average B&A pedestrian volumes

Bonteheuwel Station has a dual function and acts as an origin station for the Bonteheuwel residential area to the south, as well as a destination station for the Epping Industrial area to the north of the station as well as to the schools in the area. Bonteheuwel Station is currently a significant rail-to-rail transfer station as it is the first station that accommodates the Sarepta line for the Kapteinsklip and Khayelitsha line commuters.

Maitland Station on the other hand, acts as destination rather than origin station (as more passengers alight than board in the morning peak period) with high intensity residential and commercial land uses in close proximity to the station. A large number of passengers however also board the train at Maitland station in the morning, many transferring from the taxi rank, located immediately north of the station.

3.1.7 Data Recording Equipment

As identified in Subsection 3.1.5, video recording was selected as the primary measurement technique for obtaining the empirical data. The consumer level digital video (DV) cameras have become very popular during the last few years and as a result, video camera prices have come down to a level that enabled the purchase of several such cameras for use in this research project.

The image quality of even the smallest DV cameras is approximately one million pixels. However, since this is not the primary use of these products, there were some technical aspects that needed to be considered as follows:

- The cameras need to be as light (and small) as possible to allow flexible mounting in the field.
- Certain consumer level cameras have automatic power saving features that turn off the power when the camera is idle for a certain time that cannot be deactivated. The wireless remote control devices can be used to keep the cameras on before the beginning of the tests.
- The length of the DV tapes restrict recording to one hour. Since the cameras are to be calibrated at the start of each recording, another tape cannot be inserted without having to re-calibrate the camera viewing position.
- Battery power becomes an issue for recording longer than one hour.
- The standard camera viewing angles may restrict pedestrian measurement area sizing.
- Standard DV cameras are not waterproof devices and cannot be used outdoors in inclement weather conditions.
- Carrying and operating expensive video equipment within railway station environments is a potential theft/security risk.

During the initial stages of this research project, two miniature wireless and battery powered PAL surveillance cameras no bigger than a small cell phone were purchased purely to test the potential application of the device. The video camera transmits video signal data via a 2.4GHz radio link to a remote Digital Video Receiver that has standard RCA video/audio output sockets enabling recording directly onto a laptop in DV format (720 x 576 pixels, interlaced at a 25 fps capture rate).

The miniature camera size permits the researcher to position the cameras at concealed viewpoints, whilst keeping the receivers/recorders at more accessible and discrete locations. The difficulty of using the radio receiver is that it required mains electricity, the video angle could not be adjusted and a method to secure the device in windy conditions was necessary. The fact that the receiver required mains power meant additional resources were required in the recording setup process. Whilst the size of the miniature radio DV cameras lends itself to discrete recording, the combination of the factors mentioned above led to the use of standard DV cameras.

3.1.8 Privacy and Ethical Issues

From the literature review, it was found that other researchers were not permitted to undertake station pedestrian observations due to privacy issues and had to resort to controlled experiments (Daamen and Hoogendoorn 2003). The pedestrian observation guidelines proposed in this study are reviewed against the provisions made within the South African "*Access to Information and Protection of Privacy Act*", Act 5/2002 and amended Act 5/2003 (Government Notice 2003).

The following paragraphs identify pertinent sections found within the Act that apply to the particular survey method proposed and explains how each have been handled:

Currently, under Section 2(1) of the *Acts* (Government Notice 2003), the definition of the term "*record*" includes books, documents, maps, drawings, photographs etc., excluding videotapes but includes recording by electronic means. Under Part I, Section 2(1), the *Act* states, in part, that "*personal information*" means recorded information about an identifiable individual and includes information relating to the race, national or ethnic origin, colour, religion, age, sex, sexual orientation or marital or family status of the individual. As video footage records images of individuals, such images are capable of identifying particular individuals and therefore qualifies as "*personal information*" under the *Act* (Cavoukian 1998).

In the actual pedestrian surveys conducted in this study, there was no link to personal names or identities, and no factor could be identified directly or through identifiers linked to the subject. Since the personal identity of occupants was not important to this study, it was not the intention of this study to in any way collect information that could lead to their identification. It was the overall capabilities of the population that was of interest.

Section 29 of the *Act* (Government Notice 2003) states that collecting personal information can be motivated under five criteria. The most important criteria applicable to support this research, is if the information to be collected "*is necessary for the function and activity of a public body*". With reference to this study, this criterion can be considered applicable in the context of this research if it is considered that, "*public body*" refers to the rail authority, viz. PRASA in this case.

Section 30(2) of the *Act* (Government Notice 2003) states that the person from which personal information is intended to be collected must be informed and that the subject person has legal authority for collecting the information. This clause is however not applicable if the data collection process is affected by the

"*Hawthorne effect*" i.e. if it is deemed that notifying the persons will result in the "*collection of inaccurate information*", or "*defeat the purpose of*", or "*prejudice the use for which the information is to be collected for*" as stated in Section 30(3)b of the *Act.*

Section 33 of the *Act* (Government Notice 2003) states that there must be no unauthorised access to the data or disclosure of the data and Section 36 states that, with regard to the collection of personal information, only data for the purpose the information was originally applied for can be collected. For the purposes of this study, there can be no question that the data has been gathered for purely research purposes.

It is often argued that individuals cannot have a reasonable expectation of privacy in public places, especially in the case of urban mass transit systems where large volumes of people are concentrated in relatively restricted places. However, as indicated in terms of Sections 33 and 36 of the *Act*, people do have the right to expect that their personal information will only be collected for legitimate, limited and specific purposes; that the collection of their personal information will be limited to the minimum necessary and that their personal information will only be used and disclosed for the specified purposes.

The area of video surveillance presents a difficult subject matter for privacy officials to grapple with impartially because it is inherently privacy-invasive due to the potential for data capture. Despite that fact, there are nevertheless legitimate uses for video surveillance, as outlined in this subsection, that render it compliant within the South African Privacy laws.

It can be concluded that the collection of personal information through the use of covert video surveillance for research purposes complies with the various sections discussed above under the *Act.* It nevertheless remains incumbent upon the researcher and PRASA to govern the video surveillance system in a manner that placed a high regard for the privacy of its passengers.

The proposed video surveillance protocol, maintained during the observational phase of the study, follows the recommendations by Cavoukian (2007), and is listed as follows:

(a.) Provision of a written policy with regard to the access, use, disclosure, retention, security and disposal of records in accordance with the *Act*,

(b.) Provision of a written methodology regarding the system equipment, including location of the reception equipment,

(c.) Selection of which personnel are authorised to operate the system and access the storage device and the times when the video surveillance will be in effect,

(d.) All video recording material is to be destroyed at the end of the study,

(e.) Aim to minimize privacy intrusion by recording only what is necessary,

(f.) Video cameras are not to point at windows of other buildings nor located in places where higher degree of privacy is expected e.g. toilets.

(g.) Reception equipment must be in a restricted area and information must not be retained or used for purposes other than proposed in this study, (h.) The station managers are to be notified of the research team well in advance of the survey activities to ensure minimum disruption during the actual survey.

Towards satisfying the requirements of the various Sections in the *Act*, a written video survey protocol document was submitted on 6 November 2009 and approved by PRASA prior to engaging in any survey activity. A confidentiality agreement, attached in Appendix B, was also signed with PRASA on 26 January 2010 to ensure overall data confidentiality and transparency.

3.2 Data Collection

3.2.1 Introduction

The primary objective of collecting the empirical data was for the determination of the fundamental macroscopic relationships on level terrain (i.e. platforms and walkways) and on stairs.

Secondary measurements that were possible from the video recordings were B&A behaviour, dwell times (D_t) and Passenger Arrival Rates (*PAR*). Secondary measurements are so defined because they are derived from video recordings specifically targeted at identifying primary characteristics.Seven aspects with regard to the data collection process followed or considered are listed as follows and are discussed in greater detail in the following subsections.

3.2.2 Sample Size Requirements

Determining an appropriate sample size for this study was inevitably somewhat problematic despite the general rule; "*the larger the sample, the better*" (Verster 2004) and in this instance, there is "*unfortunately no straightforward and objective answer to the calculation of sample size*." (COCT 2004)

Due to the labour intensive nature of the data capture, collection and data assessment process, the sample size needed to be practical and manageable, but still have some degree of statistical significance. In studies on rail end-user perceptions in Cape Town, Verster (2004) found that a sample size of between 0.25 to 1% of passengers was found to be representative of the user population. It is noted that the Verster study had a population sample n = 1,696 and so would adequately represent an overall population of up to 678,400 people.

In Subsection 3.1.6, it was already identified that the peak hour volumes occurred in the morning period with daily volumes of approximately 36,000 and 55,000 passengers for Maitland and Bonteheuwel Stations respectively. Using the 1% sample rule, a sample size of 550 people per day would be statistically representative of the user population.

Instead of deciding on an adequate sample rate, it was eventually decided that two video recording sessions per measurement area type would be recorded for both morning and afternoon peak hours. This represents four hours of recorded video material per measurement area. With six measurement areas, a potential total of 24 hours of video was envisaged. The sample size achieved using this method are described in detail in Appendix E.

3.2.3 Data Recording Method

The approach to collecting the walking speed and flow data from video recording footage used in this research is consistent with that adopted by other researchers (Lu *et al.* 1990; Cheung and Lam 1997/8; Makris and Ellis 2002; Daamen 2004, Willis *et al.* 2004) where video recording techniques were successfully employed.

For the purposes of this study, purpose-built pedestrian tracking software ("*Headrecorder*") was developed together with the assistance of the Department of Computer Science at the University of Stellenbosch. This software allowed the researcher to track the co-ordinate position changes of individual pedestrians with time. A benefit of the software developed in this study is that it uses continuous video frame tracking and does not require frame-by-frame image extraction as required by the tracking systems developed by Teknomo *et al.* and Willis *et al.* This is both user friendly and allows for easy error correction.

3.2.4 Measurement Areas

Pedestrian data collection through video recordings focused on a pre-marked and measured pedestrian area defined as the "*measurement area*" (MA). In all cases, the video camera views were from above but not necessarily from vertically above. The measurement area rectangle was projected vertically to produce a measurement plane at an average adult top-of-head height of 1.65 m. This was achieved by placing grid markers on the corners of the measurement area marked at 1.65 m from the base point using a spirit level as indicated in Figure 3.2.

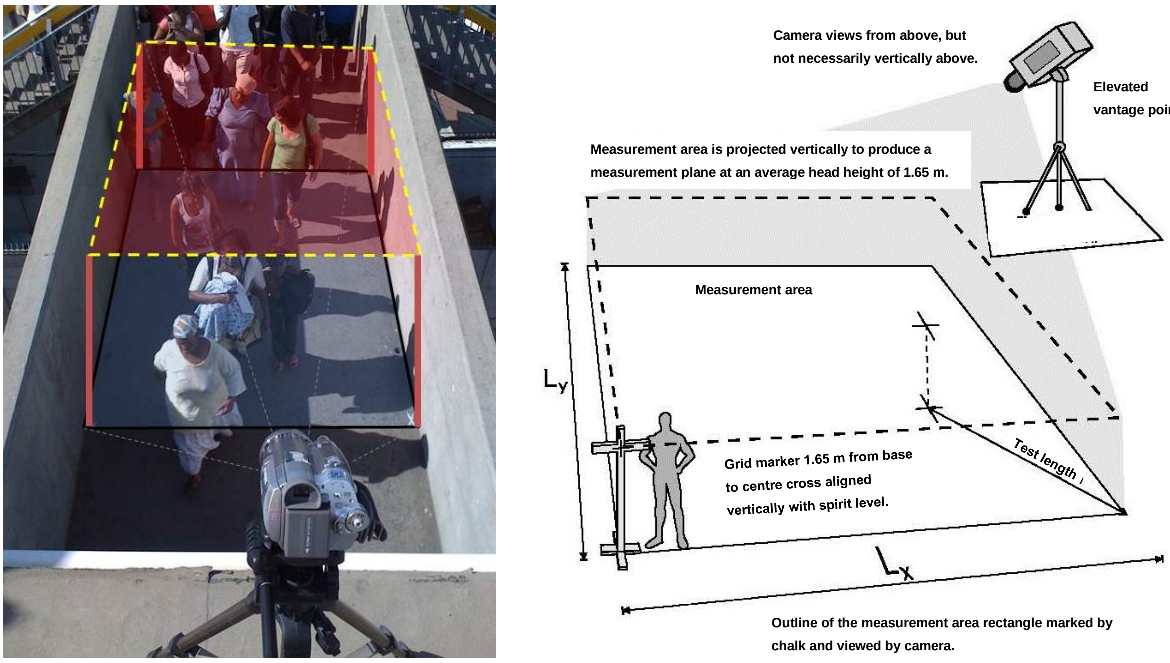


Figure 3.2: Example of a "*Measurement Area*" and projection of the measurement plane; (Source: Thompson 2004)

According to Pheasant (2002), the 1.65 m height range selected represents the average person height range for the world population. All measurement areas were also located at least 0.5 m away from the closest obstacle/s in order not to influence pedestrian behaviour in accordance with the recommendations made by Stucki *et al.* (2003).

For the purposes of gathering pedestrian behaviour data specific to certain infrastructure types within the station environment, three types of walking facilities were identified and targeted as potential measurement areas.

The platforms and skywalks presented the simplest measurement area due to the flat plane. The staircases presented a particular complication in that the stairs constitute an upper staircase flight, a horizontal landing and a lower staircase flight. In order to truly represent the staircase measurement area as a plane parallel with the stair angle, only the top flight of the staircase was considered. Selection of the lower staircase flight was not included for observation purposes due to unacceptable measurement angle errors that is introduced resulting from the combination of the vertical and horizontal distances from the camera location to the far extents of the measurement area.

Although there are only three infrastructure types that were considered for video recording observations, a total of seven measurement areas were eventually observed due to the variations in staircase and skywalk widths at the two stations. The location of the various measurement areas (MA) and area legends are also shown in Figure 3.3 for both stations.

(a.) Bonteheuwel Station *(b.) Maitland Station*

Figure 3.3: Measurement area (MA) locations at Bonteheuwel and Maitland stations; (Source: Google Maps)

Table 3.8 shows the measurement area (MA) sizes and other details for each of the areas observed. There are two measurement areas for Area "A", which resulted from the need to accommodate a different camera location. This is however not critical as the macroscopic results are presented on an area basis. In terms of selecting the actual dimensions used for each of the measurement areas, the biggest area was measured out on site that the 1.65 m elevated plane could fit within the confines of the video viewing frame. It was found that it was not possible to view the full extent of the staircase measurement area (i.e. upper flight) without fitting a wide-angle lens.

Table 3.8: Measurement area (MA) dimensions

Station	Infrastructure	Area	Period	Date	Measurement area (*A*): (Width x Length)
Bonteheuwel	Skywalk	A	PM / AM PM	Dec 2009 Dec 2009	2.5 m x 6.0 m = 15.0 m^2 2.95 m x 4.23 m = 12.48 m^2
	Platform	B	AM PM AM	Dec 2009 Dec 2009 Dec 2009	4.11 m x 5.16 m = 21.21 m^2
	Stairs	C	AM/PM	Feb 2010	2.53 m x 4.8 m = 12.14 m^2
		D	AM/PM	Feb 2010	4.5 m x 4.8 m = 21.6 m^2
Maitland	Platform	G	AM AM	Dec 2009 Dec 2009	3.83 m x 3.5 m = 13.41 m^2
	Skywalk	E	PM AM AM	Dec 2009 Dec 2009 Dec 2009	2.7 m x 3.43 m = 9.26 m^2
		F	PM	Dec 209	2.7 m x 2.53 m = 6.83 m^2

Microscopic simulations conducted by Hoogendoorn *et al.* (2007) produced density results for various time intervals and observation (or measurement) areas and revealed that shorter time periods reduce density fluctuations and on average give a better picture of the situation.

As a result of their simulation experiments, they recommended the following observation standard (forthwith defined in this study as the Hoogendoorn rule[30]):

$$n_{60}.\ A \geq 10$$

where n_{60} is the number of times per minute that the density in the measured walking area (*MA*) is determined and *A* is the area of the measurement area in m^2.

Therefore, for a measurement area (*A*) of 5.0 m^2, the density measurement observations must be determined at least for every 30 seconds. From Table 3.8, the smallest measurement area (Area F) is 6.83 m^2 and applying the Hoogendoorn rule reveals a minimum assessment time interval of 40 seconds.

Geometric details of each of the measurement areas are included in Appendix F. Note that for measurement area “A”, (viz. the Bonteheuwel skywalk), the area is located closer to the edge where the turnstile battery is located as this is the side pedestrians tend to walk on at lower density conditions. A photograph showing the video camera placement on the concourse roof in preparation for video recording of the skywalk (Measurement area “A”) is included in the appendix.

3.2.5 Measurement Observation Angles and Error

Observational accuracy is dependent on three criteria, viz. camera elevation above the measurement area, measurement area length and observation angles at the closest and furthest end of the measurement area. Figure 3.4 shows the how the observation angles (*OA*) are defined as a function of camera height and horizontal distance using measurement area "F" as an example. In the figure, the location of the measurement area is shown as the yellow highlighted line.

The observation angles (*OA*) are defined as the angle the camera view plane makes with the horizontal for the near edge (OA_{max} viz. the maximum angle) and for the far side of the measurement area (OA_{min} viz. the minimum angle). From geometry, it is clear that the camera distance should be kept to a minimum and the measurement area length should not be too large to make the OA_{min} angle too acute. The more acute the OA_{min} angle, the more difficult it becomes to observe horizontal distance off the video footage.

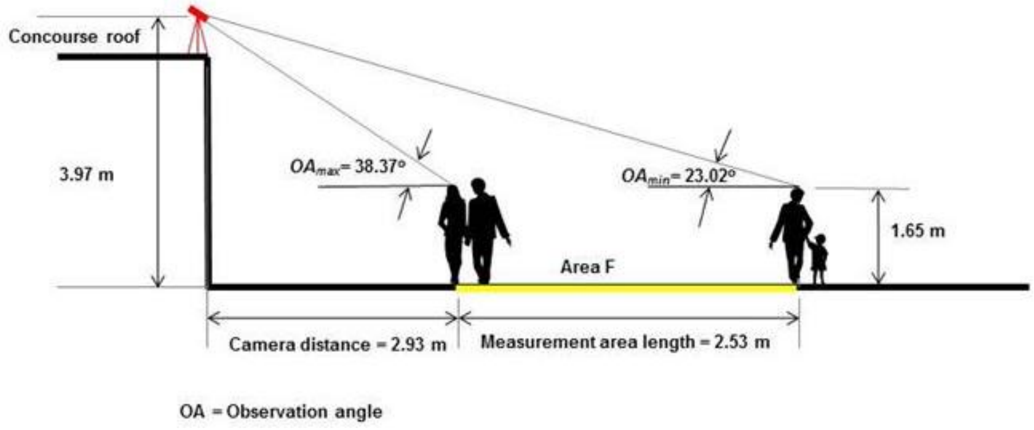


Figure 3.4: Definition of observation angles (*OA*) for measurement area "F"

Figure 3.5 shows the how the sloped observation angles (*OA*) are defined for the south staircase at Bonteheuwel Station, using measurement area "D" as an example. The observation angles are defined as the angle the camera view plane makes with the stair slope plane for the near edge (OA_{max} viz. the maximum angle) and the far side of the measurement area (OA_{min} viz. the minimum angle).

As with the horizontal measurement area, the OA_{min} angle becomes acute very quickly with increasing camera distance due to the slope of the stairs. The acute angle at the base of the stairs contributed to the reason for restricting observations to only the top flight of stairs.

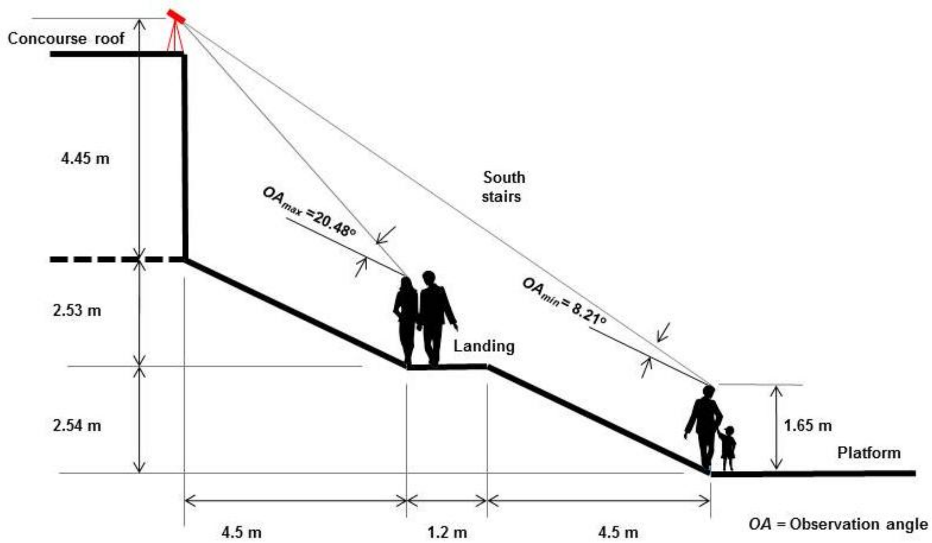


Figure 3.5: Definition of staircase observation angles (*OA*) for measurement area "D"

In order to quantify the error caused by the observation angles (*OA*), measurement area length error (*MAL'*) is introduced and defined as follows. The tracking of each pedestrian is done at the virtual head measurement plane, viz. 1.65 m above ground level. If the head of a pedestrian is tracked who is either shorter or taller than 1.65 m, then a certain amount of error is introduced. Figure 3.6 shows how measurement area length error (*MAL'*) is defined for a 1.8 m tall person entering and exiting the measurement area.

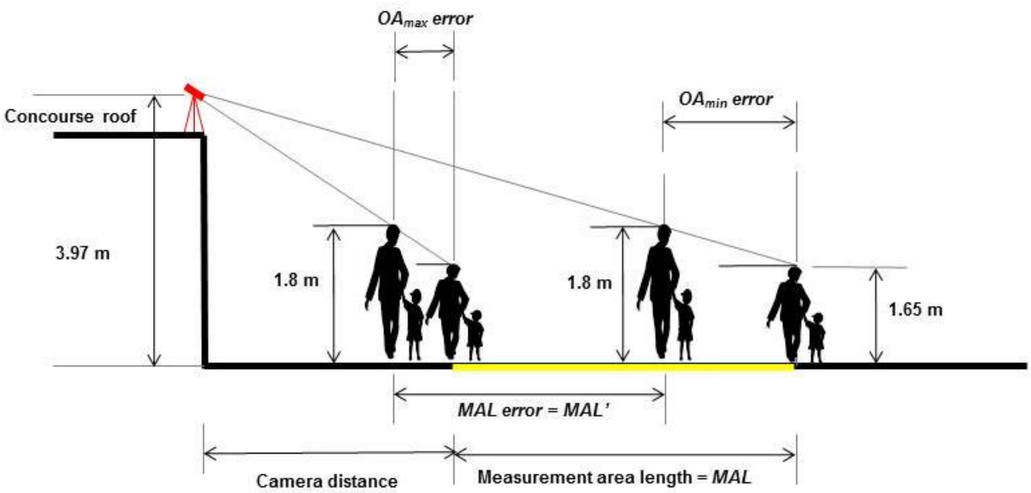


Figure 3.6: Definition of staircase measurement area length error (*MAL'*)

A taller person will be tracked sooner when entering the measurement area (*MA*) but will also exit the measurement area sooner if walking away from the camera. Conversely, a shorter person will be tracked to enter the measurement area later but will also exit the measurement area later than the person of reference height, again assuming the person is walking away from the camera.

The error is then determined according to the horizontal distance that a 1.65 m ± 150 mm person height is projected using the difference of the maximum and minimum observation angle errors as follows:

$$\%\ MAL\ Error = \frac{100\ (MAL' - MAL)}{MAL}$$

where

$$MAL' = MAL + OA_{max}error - OA_{min}error\ (if\ person\ height > 1.65\ m)$$
$$MAL' = MAL - OA_{max}error + OA_{min}error\ (if\ person\ height < 1.65\ m)$$

and

$$OA_{max}error = \frac{0.15}{\tan(OA_{max})}$$

$$OA_{min}error = \frac{0.15}{\tan(OA_{min})}$$

For each of the various measurement areas, a percentage MAL error was calculated for a 1.65 m ± 150 mm height range difference. Table 3.9 shows the various measurement area errors calculated for each of the infrastructure measurement areas.

Table 3.9: MAL errors for a 1.65 m ± 150 mm person height range for each of the observed infrastructure areas

Infrastructure	Station	Area	Camera height	OA_{max}	OA_{min}	MAL	% MAL error
Skywalk	B/heuwel	A	4.45 m (2/4 Dec '09) 4.45 m (10 Dec '09)	37.49° 39.72°	16.21° 20.22°	6.0 m 4.23 m	±5.34% ±5.36%
Platform	B/heuwel	B	9.4 m	63.23°	40.51°	5.16 m	±1.94%
Stairs	B/heuwel	C/D	6.98 m to 9.52 m (Dec '09)[bot] 4.45 m to 6.98 m (Feb '10)[top]	20.48° 62.11°	8.21° 21.94°	5.7 m 4.8 m	±11.19% ±6.10%
N Skywalk	Maitland	E	4.62 m	44.71°	24.79°	3.43 m	±5.05%
S Skywalk	Maitland	F	3.97 m	38.37°	23.02°	2.53 m	±6.47%
Platform	Maitland	G	9.57 m (10 Dec '09)	57.48°	42.81°	3.50 m	±1.89%

MAL : Measurement area length — [bot]: *Bottom flight of stairs*

OA : Observation angle — [top]: *Top flight of stairs*

For the moment, consider that the 6.0 m long measurement area "A" will be covered in 5.0 seconds by a 1.65 m tall person at an average walking speed of 1.2 m/s. Due to the observation angle error, a 1.8 m tall person would be observed to cover the same distance in 4.73 seconds at the same speed, a difference of 0.27 seconds. Since the pedestrian tracking undertaken in this study has been conducted in intervals of 10 frames, or every 0.4 seconds, it is the therefore the tracking interval that becomes the critical criteria and represents a maximum 8% error (0.4 / 5.0 seconds) for the measurement area length (% *MAL* error).

For our research purposes, *MAL* error targets of ±8% or less are considered acceptable for the 1.65 m person reference height. As speed is calculated as distance over time, the % *MAL* error would correlate to a corresponding error in time lapse within the true measurement area length (*MAL*) and hence overall speed measurement.

This exercise revealed that the staircase observations done in December 2009 for the full flight of stairs introduced errors exceeding the acceptable 8%, which was reduced to 6.10% by considering only the upper flight of stairs. As shown in Table 3.9, all the other *MAL* errors were considered acceptable below the 8% level.

3.2.6 Details of Pedestrian Surveys Conducted

Pedestrian surveys were carried out during the months of December 2009 and February 2010 with the first survey, conducted on 2 December undertaken as a pilot study to check the performance of the equipment and establish camera settings. At the beginning of each survey, the three video cameras were positioned on the concourse roof with tripods.

The measurement areas were then measured and marked out on the ground with white chalk, which allowed the same reference points to be used in the ensuing days. In order to keep the measurement area inconspicuous, it is was decided not to demarcate the entire measurement area on the ground and so only the corners of the area was marked out. All cameras were set to start recording approximately five minutes before the start of the selected peak observation period. This was done to ensure that all of the camera devices were properly functioning allowing sufficient time to attend to hardware errors before the start of the peak period.

Once the cameras were in position, an assistant on the ground would then place the 1.65 m long calibration stick on the four pre-marked corners of the measurement area to ensure that the virtual plane corners were in fact within the cameras field of vision. The process was repeated for the remaining measurement areas. Once this calibration process was complete, it was a matter of waiting for the start of the peak hour period before beginning the recording. Video recording was permitted to run uninterrupted for one hour before terminating the survey.

In order to avoid significant differences in pedestrian behaviour for different times of the day observed by Willis *et al.* (2004), survey times for the morning and afternoon peaks at the two locations were kept consistent for the duration of the survey. The B&A sample indicated in the table refers to the *number of times* on the particular tape where it was possible to record boarding and alighting activities and does not represent the number of pedestrians observed in the B&A process.

Appendix H provides a sample of the Excel datasheet for capturing the B&A observations which were reviewed frame-by-frame using commercial video software. Whenever a passenger passed the virtual plane representing the coach door opening, the video time stamp[53] in "*hh:mm:ss*" format was copied to the excel spreadsheet, together with the direction of the passenger viz. either "*b*" for a boarding passenger or "*a*" for an alighting passenger. Train stop and departure times were also recorded in the "*hh:mm:ss*" format. The door sample refers to the observed coach door as occasionally it was possible to collect data for two doors from the same video footage.

From the sample capture sheet provided in Appendix H, it can be seen that passengers sometimes alighted before trains stopped which should not be considered as an error in the data capture process as this occurred frequently. It was also observed that when a train is heavily loaded, standing passengers at the doorway would need to alight in order to make way for other passengers inside the coach to disembark. This passenger would then normally board again after completion of the alighting process and is defined as a "*courtesy exit*"[12] and was identified in the "*comments*" column if this occurred.

3.3 Data Verification and Processing

This section describes how the video data was processed from a raw format to a quantitative format. The data processing essentially incorporated the semi-automatic tracking of each pedestrian head from the moment they entered the measurement area (MA) until they exited. The tape was then rewound and the process was repeated until every pedestrian moving in the measurement area for the duration of the recording was tracked.

Other researchers including Virkler and Elayadath (1994) have used fully automatic methods to detect and track pedestrians on video files. They demonstrated that the performance of these fully automated methods can be excellent at low densities or when participants are equipped with devices to facilitate their classification. Unfortunately, the existing state-of-the-art automatic recognition and tracking technology does not yet permit the proper and speedy tracking of individual pedestrians in crowded environments like metro stations where low ceilings often force the use of surveillance-type cameras set at acute angles often in poor light conditions.

3.3.1 The Development of Pedestrian Tracking Software

With the kind assistance of the Computer Science Department at the University of Stellenbosch, such software was produced over a four month period with work done on several versions and updates between August 2009 and April 2010 as follows:

<u>Version 1: Basic “Headrecorder” program: Released on 14 August 2009</u>
The first version of the program was developed in OpenCV format, specifically designed for semi-automatic head tracking and data extraction.

<u>Version 2: Introduction of “Headplayback” module with 2D playback: Released on 27 August 2009</u>
With version 1, it was found that “*Headrecorder”* could not open video files of one-hour duration. It was therefore necessary to use another freeware program “*Any Video Converter”* to convert the recorded camera video to the xvid codec to make it readable.

<u>Version 3: Introduction of “Headplayback” module with 3D playback: Released on 20 November 2009</u>
In version 2, during the 2D playback video, the graphic representation of the pedestrian heads needed to be corrected since they overlapped each other in dense situations.

The user manual for the “*Headrecorder”* and “*Headplayback”* software is included in Appendix I.

3.3.2 Video Head Tracking

An essential part of using video footage is the ability to extract data from the (digital) images. This subsection discusses the tracking technique used in this research.

As mentioned in the previous subsection, a purpose built software programme suite constituting "*Headrecorder*" and "*Headplayback*" applications was specifically developed for this research. The "*Headrecorder*" programme allowed for the semi-automatic tracking of each head within the measurement area per pre-selected frame rate. The camera equipment recorded video at 25 frames per second (fps), equivalent to 0.04 seconds per frame.

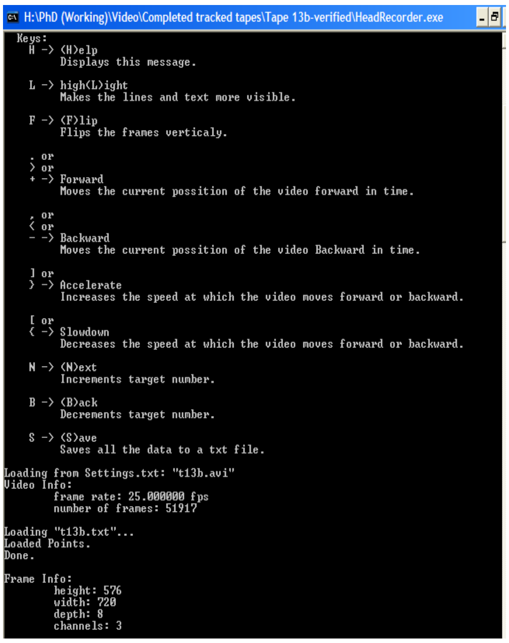
To reduce tracking workload, a frame interval of 10 frames was selected for tracking purposes, meaning that a person was tracked every 0.40 seconds, which was considered adequate for our purposes. A person walking at an average speed of 1.2 m/s would cover a distance of 0.48 m during this time.

The different steps of the head tracking process included the following:

1. Converting raw digital video recordings obtained from the DV camera tapes to a digital "*avi*" format.
2. Identifying the head position of target pedestrians using the "*Headrecorder*" software, with the aim to also identify and record the different pedestrian attributes of the particular target person.
3. Identifying and tracking pedestrian trajectories for each subsequent selected frame. This approach determines the screen x, y co-ordinates of the pedestrian's head.
4. Mapping of screen image co-ordinates to terrestrial coordinates. Conversion to real-world coordinates was achieved by linear scaling, using the terrestrial coordinates of the corners of the measurement area as reference coordinates.

Figure 3.7 (*a.*) shows the screenshot of the "*Headrecorder*" programme and Figure 3.7 (*b.*) shows the additional editor interface screen. An example of a sample output text (".txt") file is included in Appendix J. The text (".txt") file essentially consists of the ID no, screen co-ordinates and associated frame number.

(a.) Tracking video interface



(b.) Editor interface

Figure 3.7: Screenshot of the "*Headrecorder*" tracking screen and editor interface

During the tracking process, it was necessary to identify "*markers*"[34] within the pedestrian behaviour observed, which included persons undertaking/exhibiting the following behaviour:

- Person/s selling or purchasing items, tarrying[52], stopping, waiting or suddenly changing direction;
- Person/s with severe disabilities, riding or pushing a bicycle;
- Person/s that have less than three tracking co-ordinates within the MA;
- Person/s that walk along the edge of the MA boundary. This caused the analysis programme to erroneously include and/or exclude certain tracking points leading to faulty measurements;
- All children less than 15 years old;
- All persons within the MA at the beginning and termination of the observation frames. This was done in order to define the start-up density;
- Person/s whose gender was unclear for whatever reason;
- Person/s with large headgear that made uniform head tracking difficult;

3.3.3 Parameter Extraction

The text file output of the "*Headrecorder*" tracking program (enclosed in Appendix J) provided only pedestrian ID numbers and the respective screen (image) co-ordinates of the pedestrian head for every frame interval selected in the video. Although this presents very useful raw data, the analysis thereof required significant data manipulation.

Towards the analysis of the raw data, a macro[32] program ("*Pedestrian Tracking Analysis*") was written in Visual Basic to operate within the Microsoft Excel environment. The macro algorithm involved reading the longitudinal raw data, identifying the pedestrian ID number, taking the associated x and y coordinates, frame number and associated pedestrian attributes observed to a more manageable Excel format. The structure of the spreadsheet and associated macros is shown in Figure 3.8.

As shown in the flowchart, the input data required by the spreadsheet includes four data sheets described as follows:

<u>Tracked data:</u> This data is the raw text file co-ordinate output data provided by the "*Headrecorder*" software (i.e. the x and y co-ordinates of each individually tracked pedestrian). The data is imported into Excel as a delimited text file.

<u>Attribute data</u>: This data specifies the gender, person size, group size, encumbrance and movement type associated with each pedestrian ID tracked.

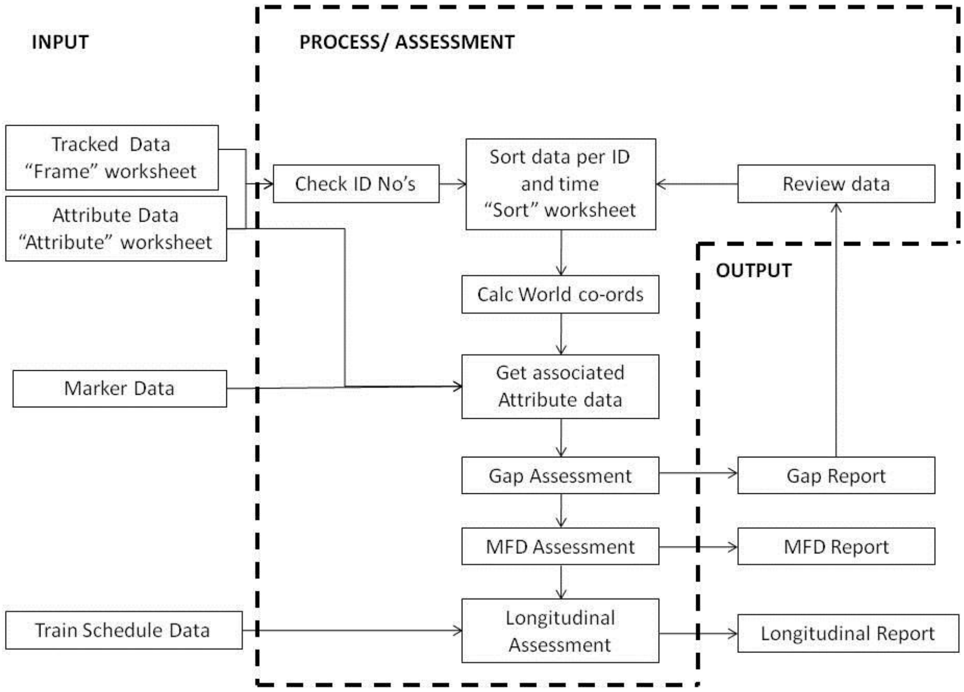


Figure 3.8: Structure of "*Pedestrian Tracking Analysis*" spreadsheet and various macros

Marker data: This is a spreadsheet indicating additional markers observed on a frame-by-frame basis to be considered in the analysis.

Train Schedule data: This spreadsheet provided the exact time calculated from the video frame of when trains arrived (stopped) and departed.
The macro algorithm then needed to incorporate the following data checks on this input data, under the Process or Assessment stage (refer to Figure 3.8) as follows:

- Check that the pedestrian ID's tracked (from the "*Headrecorder*" program) coincided with the ID no's observed and recorded in the "*Attributes*" worksheet and that there were no discrepancies.

- Once this was done, the "*Headrecorder*" data was then sorted according to increasing ID no's and then according to increasing frame numbers. The sorting process also selectively excluded tracked points that fell outside the measurement area.

- Once the data was sorted, then world coordinates were calculated for each individual pedestrian tracked record. Calculation of real world coordinates from the image coordinates is described in further detail in Subsection 3.3.5.

- Once world coordinates were calculated, then the associated pedestrian attribute data (including gender, person size etc.), was read from the separate worksheet and linked to the particular data record or ID no. A separate "*Marker*" file was also incorporated at this stage into the attribute association. The file purely identified additional "*marker*" type pedestrians within the measurement area and identified the frame numbers for which they needed to be incorporated within the MFD calculation.

- The macro incorporated a "*Gap assessment*" of the tracked data to identify "*missing*" or "*single*" pedestrian ID's. "*Missing*" ID's refer to a gap in the tracking process where the data-capturer failed to click at least one intermediate frame in the tracking process and so no coordinates were written to the file for that particular frame. "*Single*" ID's refer to where the data-capturer would only click once for a pedestrian in the measurement area resulting in one set of co-ordinates for the pedestrian which would mean that the macro would not be able to calculate speed. This could occur when pedestrians are running very fast and/or running diagonally across the corner of the measurement area. The results of this analysis was written to the "*Gap report*" for further action.

- All persons that crossed the "*entry*" line of the MA were checked that they in fact crossed the "*exit*" line. If this did not occur (e.g. where pedestrians did u-turn movements) then the data was not used and the associated pedestrian record was converted to a "*marker*" status.

- Once the Gap Assessment had been done and all data gaps corrected, then the macroscopic fundamental attributes of speed, density and flow rates were calculated and written to the "*MFD Report*" worksheet.

- The data in the MFD report provided the fundamental statistics for each of the individually tracked pedestrians. The final output stream included a time interval based dataset that provided a running time record of the density and flow criteria for the MA.

Note that the full range of pedestrian attributes, as described in the previous subsection, was only conducted for the platform observations, since the sample was both reasonably small viz. n = 3,452 pedestrians, and the densities allowed for the identification of the parameters not possible at higher densities.

Table 3.10 shows the details of the platform database into "*alighting*", "*boarding*", "*waiting*" and "*marker*" movement classifications.

Table 3.10: Details of tracked platform data

Tape	**Time**	**Date**	**Station**	**Sample size (*n*)**	**"*Movement Type*" sample size (*n*)**			
					Alighting	**Boarding**	**Waiting**	**Marker**
1c	PM	2 Dec 2009	B/heuwel	93	4	10	35	44
4	PM	3 Dec 2009	B/heuwel	819	230	67	265	257
6	AM	4 Dec 2009	B/heuwel	527	374	7	79	67
16	AM	10 Dec 2009	Maitland	486	416	8	34	28
22	AM	11 Dec 2009	Maitland	541	447	4	43	47
26	AM	2 Feb 2010	B/heuwel	470	285	1	96	88
28	PM	2 Feb 2010	B/heuwel	519	132	10	236	141
			Totals	**3,455**	**1,888**	**107**	**788**	**672**

For the platform observations, if the enumerator could not identify the pedestrian movement type i.e. either "*boarding*", "*alighting*" or "*waiting*", then the person would be tagged as a "*marker*". Also, only those pedestrians who continued to walk through the measurement area were considered or tracked. Those pedestrians that hesitated, stopped or executed any other behaviour not commensurate with walking activities were also tagged as "*markers*". Table 3.11 shows the gender and marker sample details for the walkway (skywalk) dataset. A total sample of *n* = 11,433 pedestrians were tracked, of which 55% (*n* = 6,288) were observed at Maitland Station and 45% (*n* = 5,145) were observed at Bonteheuwel Station with an overall 58% (*n* = 6,122) male sample compared to the 42% female sample (*n* = 4,433).

Table 3.11: Details of tracked skywalk data

Tape	Time	Date	Station	Sample (*n*)	Male	Female	Markers
13	PM	9 Dec 2009	Maitland	1,129	543	233	353
15	AM	10 Dec 2009	Maitland	2,214	1,214	902	98
21	AM	11 Dec 2009	Maitland	2,945	1,632	1,205	108
2	PM	2 Dec 2009	Bonteheuwel	1,245	707	380	158
5	AM	4 Dec 2009	Bonteheuwel	1,610	1,016	560	34
18	PM	10 Dec 2009	Bonteheuwel	2,290	1,010	1,153	127
			Total	**11,435**	**6,122**	**4,433**	**878**

Table 3.12 shows the gender and marker sample details of the tracked staircase dataset. A total sample of *n* = 9,520 pedestrians were tracked on both staircases at Bonteheuwel Station. A 69% (*n* = 6,070) male sample was observed compared to the 31% female sample (*n* = 2,668). Genders of "*marker*" data points were not recorded. Note that the staircase dataset is exclusive to the Bonteheuwel Station. The "*narrow*" stairs refer to the narrower 2.53 m (northern) staircase and "*wide*" staircases refer to the wider 4.50 m (southern) staircase.

Table 3.12: Details of tracked staircase data at Bonteheuwel Station

Tape	Time	Date	Staircase	Sample (*n*)	Male	Female	Markers
27	AM	2 Feb 2010	Narrow	1,079	708	238	133
29	PM	2 Feb 2010	Narrow	1,356	822	428	106
31	AM	3 Feb 2010	Narrow	878	609	200	69
32	PM	3 Feb 2010	Narrow	1,595	975	511	109
34	AM	4 Feb 2010	Wide	1,817	1,247	440	130
36	PM	4 Feb 2010	Wide	1,846	1,021	660	165
40	AM	9 Feb 2010	Narrow	949	688	191	70
Total				**9,520**	**6,070**	**2,668**	**782**

The three basic MFD parameters of pedestrian traffic flow viz. flow, speed and density were all extracted from the recorded videos by means of the "*Pedestrian Tracking Analysis*" software developed.

The relationship between flow, speed and density, which is called the macroscopic fundamental traffic flow formula, is given by

$$q = u.k$$

where q is the flow rate (in pax/m/sec), u is the speed (in m/s) and k the density parameter (in pax/m^2). As recommended by Hall (1997), all three parameters were observed independently. The methods and formulae used to calculate the three parameters; speed (u), flow (q) and density (k) from the empirical dataset is described in detail below:

<u>Pedestrian Speed (u):</u>

The fundamental characteristics of traffic flow are flow (q), speed (u) and density (k) which can all be observed and studied at the microscopic and macroscopic levels. There are many other macroscopic pedestrian characteristics but for the purposes of this study, the main concerns are those characteristics that relate to data collection observed over a relatively short distance (i.e. the measurement area). Other characteristics such as journey distance, route choice, socio-economic characteristics etc. are not relevant to this study and are not discussed.

Walking speed is an important element of design. We have already discovered that previous researchers including Henderson (1971); Henderson and Lyons (1972); Willis *et al.* (2004), found that the free-flow speeds within pedestrian crowds are normally distributed. As explained by Teknomo (2002), there are two ways to calculate average speed, viz. using the time-mean-speed (TMS) method or by using the space-mean-speed (SMS) method. Time-mean-speed (TMS) is calculated as the average speed of all pedestrians passing a virtual line on the measurement area over a specified period. It is calculated as an arithmetic average of the spot speed or instantaneous speed (u_i), written in equation format as follows:

$$TMS = \bar{v}(t) = \frac{\sum_{i=1}^{N} u_i(t)}{N} \qquad \text{(Equation 2.12,Teknomo 2002)}$$

where N is the number of observed pedestrians and u_i is the instantaneous speed of the i^{th} pedestrian. The space-mean-speed (SMS) is the average speed of all pedestrians occupying the measurement area (MA) over a specified time period and is calculated based on the travel time for each pedestrian to traverse a fixed length, L, between the entry and exit lines of a measurement area.

If t_i^{out} and t_i^{in} represent the clock time of the i^{th} pedestrian to exit and enter the pedestrian measurement area respectively, then space mean speed (SMS), $\bar{u}$ is calculated as follows:

$$SMS = \bar{u} = \frac{N.L}{\bar{t_\imath}} \qquad \text{(Equation 2.13,Teknomo 2002)}$$

where L is the length of the measurement area, N is the number of pedestrians observed and $\acute{t}_i$ is the travel time calculated as follows:

$$\bar{t} = \sum_{i=1}^{N} (t_i^{out} - t_i^{in})$$ (Equation 2.14,Teknomo 2002)

Because of the availability of the microscopic data gathered in this study, the space-mean-speed ($\bar{u}$) shown in equation 2.13 has been adjusted to use the following definition of L as follows:

$$L = \sum_{f_i^{in}}^{f_i^{out}} d_i(\Delta f)$$

where:

$d_i\ (\Delta f)$ is the euclidean distance[19] measured between successive tracked points viz. between frame no's f_i and the following frame $f_i + 1$ for the i th pedestrian shown graphically in Figure 3.9. The overall distance is determined between frame limits $f_i^{\,in}$ and $f_i^{\,out}$ i.e. the first and the last frame that the pedestrian is observed within the MA respectively. Note that only pedestrians observed within the measurement area for the particular video frame are considered.

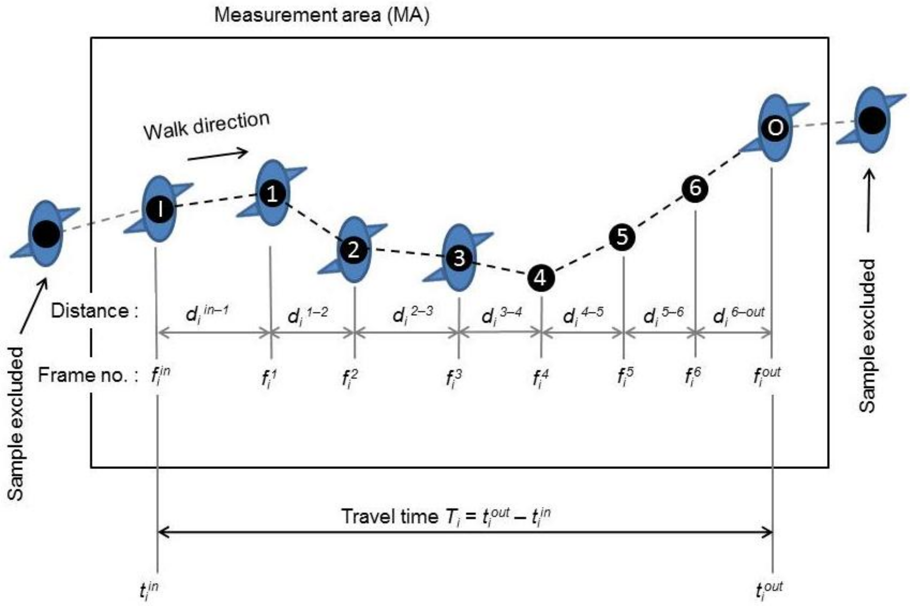


Figure 3.9: Definition of d_i for a tracked pedestrian through the measurement area

For each observation from video frame *f* to the following video frame *f+1* the travel distance d_i between these two observation frames for a particular pedestrian *i* is calculated from the tracked co-ordinates as follows:

$$d_i(\Delta f) = \sqrt{(Y_{f+1} - Y_f)^2 + (X_{f+1} - X_f)^2}$$

The travel distance was calculated for each row in the dataset provided that the person tracked appeared in both frames *f* and *f+1*. If the video started and ended with a number of pedestrians in the image, the first and last group of pedestrian observed who started or ended the walk from within the measurement area were identified as "*markers*". Average speed ($\bar{u}$) is expressed as metres per second (m/s).

It is important to note that, in this study, "individual" SMS (speeds) has been calculated over the measurement area, in accordance with the adjusted SMS equation 2.13, with each individual SMS associated with the corresponding average density and average flow rate as defined below. Individual speeds instead of average speeds of all pedestrians over the T_i time interval have been used, due to the large number of motionless ("*marker*") pedestrians frequently found in the measurement area (eg. standing or sitting at the handrails etc.), which would significantly reduce the value of *u* if taken as an average for all pedestrians. The additional motivation for using individual speed is that personal attributes (such as gender, body size etc.) can be associated with the particular individual and facilitates the development of analytical speed distribution histograms. Whilst it is not erroneous to use individual speeds, readers should be aware that using the individual speed criteria, by definition, would therefore not obey the $q = u.k$ relationship.

Pedestrian Density (*k*) :

The pedestrian traffic density is denoted by the symbol *k*. Papacostas and Prevedouros (1993) define pedestrian density as the number of pedestrians within a unit area (pax/m^2) calculated as follows:

$$k(t) = \frac{\sum_t^{t+i} N(t)}{T.A}$$

where *N(t)* is the average number of pedestrians occupying the measurement area (MA) within the time interval period *T* of assessment *(*viz. from time *t* to time *t* + *i)* and *A* is the area of the measurement area.

The reciprocal of pedestrian density is called the space-density, space module or area module, denoted by the symbol *M*, with units in terms of surface area per pedestrian (m^2/pax). The space-density is calculated as the area of the measurement area (MA) per number of pedestrians observed during a time interval *T*. The definition of space-density is:

$$M = \frac{1}{k} = \frac{u}{q}$$

From equation 2.13, the speed parameter of an individual pedestrian (*i*) was based on the time of entry (t_i^{in}) within the measurement until the last point before exiting the area (t_i^{out}). This time duration viz. $T_i = (t_i^{out} - t_i^{in})$ for the particular pedestrian to traverse the measurement area constitutes a number of smaller time intervals i.e. from time *t* to *t* + *i* corresponding to successive video frames *f* to *f*+1 respectively. Time intervals are based on the tracking frame selection rate viz. 5 or 10 frames per second. In order to associate a density value for a particular pedestrian (*i*), the average density (k_i), is then calculated as the average density, of all the densities calculated within the intervals as follows:

$$\bar{k}_i(f) = \frac{\sum_{f_i^{in}}^{f_i^{out}} k(\Delta f)}{n}$$

where:

$$k(\Delta f) = \frac{\sum_f^{f+1} N}{T.A}$$

and *n* equals the number of intervals within the time period $T = (t_i^{out} - t_i^{in})$, *N* is the number of observed pedestrians (in pax) and *A* is the measurement area (MA) area (in m^2). Density is expressed as persons per square metre (pax/m^2).

Pedestrian Flow (*q*):

Pedestrian flow rate, denoted by *q*, is defined by Lu *et al.* (1990) as the number of pedestrians that pass a perpendicular line of sight across a unit width of a measurement area during a specified period of time and normally has a unit of pax/min/m (number of pedestrians per minute per meter width). If *w* denotes the width of the measurement area and *N* indicates the number of pedestrians observed during the observation time *T*, then the flow rate *q* can be calculated as:

$$q = \frac{N}{T.w}$$

In this study, pedestrian flow was determined by electronically counting (through purpose built macros) the number of pedestrians passing a virtual line of sight across the width at the centre of the measurement area within a given time interval. For bi-directional flow, this is the total number of pedestrians counted in both directions. The following sequence provides an explanation of how the flow rate is calculated:

- In order to develop the *q* vs. *k* and *u* vs. *q* macroscopic relationships, the flow calculation was based on the individual "*target*" pedestrian traverse time interval $T_i = (t_i^{out} - t_i^{in})$. Figure 3.10 provides a graphic representation of the definition and shows four different pedestrian profiles observed in the time interval t_1^a to t_1^b. In this scenario, the time frame data for pedestrian $i = 1$ is considered. The first tracked point for pedestrian $i = 1$ occurs at time $t = t_1^{in}$ and the last point is tracked at time $t = t_1^{out}$. The figure represents the travel pattern across the measurement area from an overhead perspective and shows the exact location of three other pedestrians between these two times.

- In the figure, pedestrians $i = 2$, 3 and 4 are also shown. At the moment pedestrian $i = 1$ enters the measurement area at time t_1^a, pedestrian $i = 2$ is already well within the measurement area (MA) but has not passed the MA centreline yet. Because pedestrian $i = 2$ crosses the centreline within the t_1^{in} to t_1^{out} assessment time frame associated with that of the target pedestrian $i = 1$, pedestrian $i = 2$ accrues to the pedestrian flow rate statistics. Pedestrians $i = 3$ and $i = 4$ shown in the figure do not at any stage of the t_1^{in} to t_1^{out} assessment time frame cross the centreline and therefore are both excluded from the associated pedestrian flow rate for pedestrian $i = 1$.

- Note that each tracked point (represented by the coloured numbered circle in the figure) is based on the frame rate tracking interval selected, i.e. 10 frames (400 ms) in this instance.

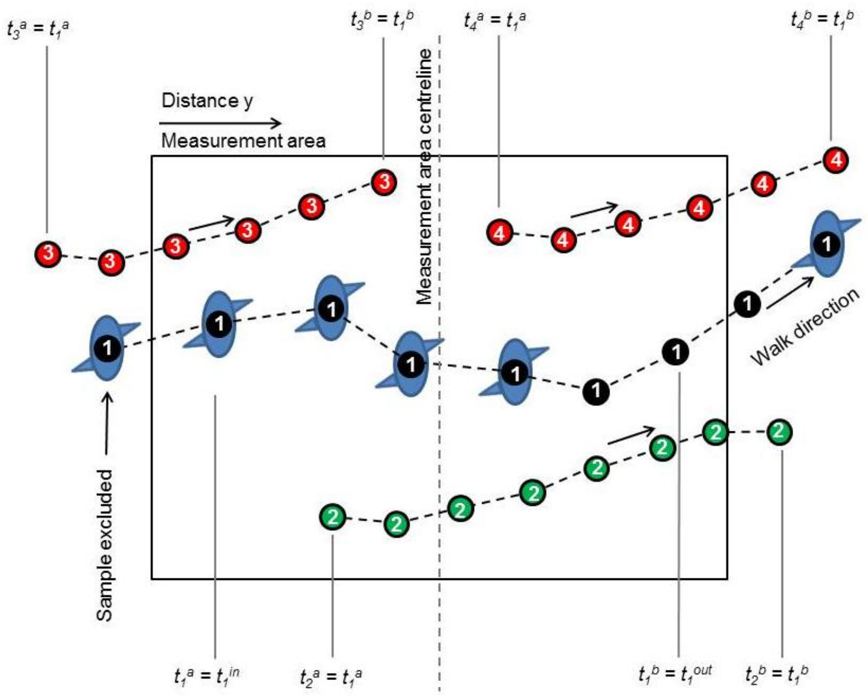


Figure 3.10: Schematic showing various pedestrian contributions towards the flow rate (*q*) calculation

- Within the t_1^{in} to t_1^{out} assessment time interval, the algorithm counts the number of pedestrians passing the MA centreline. In order to determine the flow ratio (*r*), the direction of pedestrian travel was determined using the co-ordinates of exit and entry points. As indicated earlier, pedestrians not crossing the centreline within the t_1^{in} to t_1^{out} assessment time interval were not considered as part of the flow calculation statistics attributable to pedestrian *i*.

The flow rate associated for the t_i^{in} to t_i^{out} assessment time interval (T_i) for pedestrian *i* is then calculated as follows:

$$q_i(t) = \frac{\sum_{t_i^{in}}^{t_i^{out}} N(t)}{T_i}$$

where *N* equals the number of pedestrians crossing the centreline within the time period T_i. Flow rate is expressed here as pedestrians per second (pax/sec). To ensure that the algorithm considers every scenario in the flow rate calculation, all possible combinations of pedestrian locations relative to the measurement area (MA) are considered as shown in Figure 3.11. The figure shows the applicable scenarios contributing to the flow data statistics of the reference scenario (i.e. target pedestrian) with an assessment interval t_r^{in} to t_r^{out}.

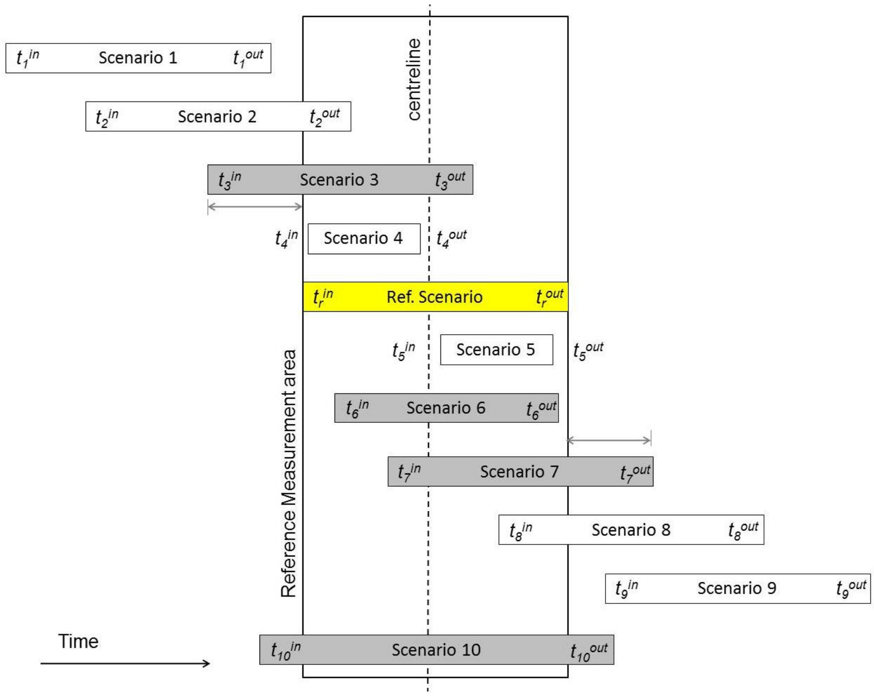


Figure 3.11: Definition of assessment scenarios for the flow rate calculation

The figure shows the ten possible scenarios for which other pedestrians find themselves spatially within, partially within or outside the measurement area during the "*reference*" assessment time period t_r^{in} to t_r^{out}. In this instance the x-axis represents both space and time. The yellow bar represents the "*reference*" pedestrian scenario within the measurement area. All white bars represent pedestrians who do not cross the MA centreline and therefore do not contribute to the flow calculation whilst grey bars show the scenarios where pedestrians cross the MA centreline and whose data therefore contributes to the flow rate calculation.

Passenger Arrival Rate (*PAR*) and Flow Ratio (*r*):

Passenger Arrival Rate (*PAR*) is essentially the platform-based flow rate *q* expressed longitudinally in order to provide an indication of the passenger arrival profile prior to train departure. Flow direction is also determined for each tracked pedestrian record (*i*). For each assessment period $T_i = t_i^{in}$ to t_i^{out}, the flow ratio (r_i) is determined as the ratio of the flow value in the direction of pedestrian *i* over the combined bi-directional flow value calculated as follows:

$$r_i(t) = \frac{q_i.(t)}{q.(t)} \qquad (3.8)$$

where $q_i(t)$ is the flow rate in the direction of pedestrian *i* and $q(t)$ is the total combined bi-directional flow rate.

3.3.4 Trimming Data into the Measurement Area

Figure 3.12 shows the co-ordinate system used for calibrating the measurement area with the top left point "A" serving as the origin point of the measurement area. The x co-ordinate system follows the Cartesian system viz. x is larger to the right, whilst the y-axis values increase towards the bottom of the screen. The screen co-ordinates are based on screen pixels with the top left of the video screen serving as the (0,0) origin and the bottom right of the video screen having (720,576) as (x, y) co-ordinates. The identification of the four corners of the measurement area is defined in an anticlockwise direction from the top-left hand corner (viz. from A, B, C and D representing real-world co-ordinates) as it appears in the screen.

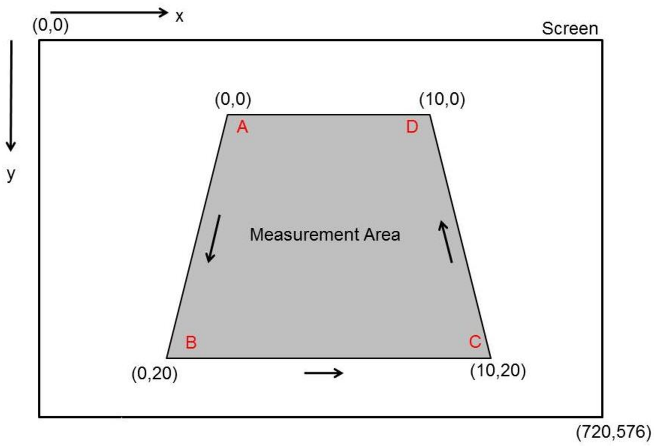


Figure 3.12: Screen (Image) and real-world co-ordinate system

In order to restrict and assess pedestrian data within the measurement area only, data trimming was done described as follows:

1. The image co-ordinates of the four corners (A', B', C' and D') that bound the real-world measurement area were obtained from the text file.
2. Linear equations for vectors A'B', B'C', C'D' and A'D' are derived using the image co-ordinate system.
3. Any pedestrian data point from the tracking database whose y_i co-ordinates plotted below line B'C' or above line A'D' or whose x_i co-ordinate plotted to the left of line A'B' or to the right of line C'D' were trimmed out from the database.

3.3.5 Calculation of Real-World Coordinates from Image Coordinates

The conversion of image Euclidean coordinates to real-world Euclidean coordinates is simply a transformation from one two-dimensional space to another two-dimensional space; the three-dimensional sophisticated camera calibrations found in literature are not needed.

Referring to the two planes shown in Figure 3.13, if a co-ordinate system is defined in each of the planes as world coordinates and image coordinates, then the central projection mapping may be expressed as :

$$x' = A.x$$

where *x'* is the destination (image plane), *x* is the original (world plane) coordinates and *A* is the perspective transformation non-singular [4 x 2] matrix that maps the co-ordinates from one plane to the other. Shape is distorted under such a perspective transformation, but since the image plane is related to the world plane via a projective transformation, this distortion can be undone. This can be done by computing the inverse projective transformation and applying it to the image, resulting in an image where the objects have their correct geometric shape.

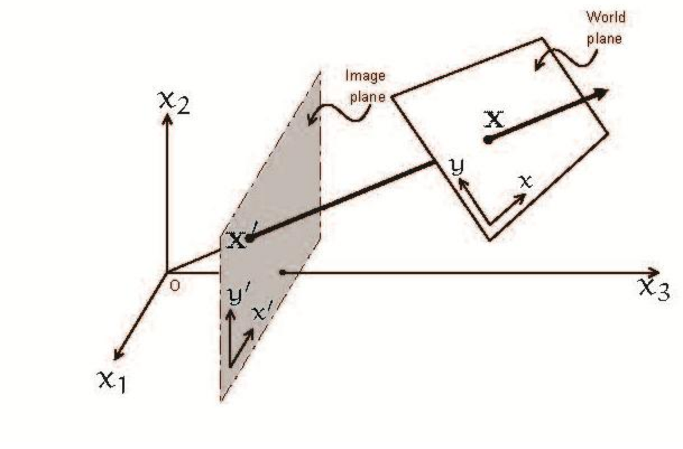


Figure 3.13: Transformation from world plane to image plane; (Source: Herbst & Hunter 2008)

In order to compute this inverse transformation, we choose local coordinates *x = (x,y)* and *x' = (u,v)* both measured directly from the world and the image plane, respectively. The transformation used for the purposes of this study is the same as the one used by Lin and Fuh (1999), as stated in literature by Gonzalez and Woods (1993) as follows:

$$x' = A.x$$

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} c_1 & c_2 & c_3 & c_4 \\ c_5 & c_6 & c_7 & c_8 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ xy \end{pmatrix}$$

It should be noted that extracting trajectory data from video footage is nothing new and has been done in the past by Berrou *et al.* (2005); Hoogendoorn *et al.* (2003); Teknomo (2002) and Willis *et al. (*2002).

3.3.6 Problems with the Data Capture Process

This subsection describes some of the issues faced and challenges that needed to be overcome as follows:

- Since the manual data capture process was manually very time intensive, obtaining resources to undertake the data capture and the motivation to continue with this tedious task was difficult.

- Enumerators occasionally struggled to identify gender in certain instances.

- Occasionally, pedestrians would not traverse the entire measurement area (i.e. enter and exit) but loiter or wait/sit within the measurement area. These persons were then tagged as "*markers*" which, although considered when calculating person densities, was excluded from the speed sample.

- Pedestrians on the stairs would occasionally lean over the railing, which resulted in the target head frame briefly projecting outside the measurement area. This had to be manually corrected afterwards.

- On platforms, three types of persons were observed, viz. those arriving on the platform waiting for trains, those boarding trains during the train dwell and those alighting trains. Each of these person types were tagged as "*Wait*", "*Board*" and "*Alight*" pedestrian types respectively. Only speeds of persons walking through the entire measurement area were considered. The remaining persons, not doing so, were tracked, but tagged as "*markers*".

- It was found that the identification of the "*group size*" attribute was also difficult in dense situations.

- During the boarding and alighting (B&A) surveys, it was occasionally observed that the doors would not open and passengers were forced to open and keep the door physically open themselves. These factors were considered in the eventual data analysis.

- In certain of the video recordings, the sun/shade border over the measurement area interfered with the video contrast settings.

Apart from the limitations stated above, potential improvements to future pedestrian tracking endeavours are:

- the identification of "*marker*" attributes that influence the pedestrian behaviour e.g. identify if markers are static or moving.

- to further classify marker types as either "*standing*", "*seated*" or "*other*" which would be useful in determining the impact of such people (e.g. seated people) on staircase capacities.

3.3.7 Boarding and Alighting Data Capture Process and Data

From video footage, it was possible to observe boarding and alighting (B&A) activity at individual coach doors. B&A analysis was undertaken as follows:

1. Video footage was played back using frame-by-frame video advancement and associated real-time clock display in "*hh:mm:ss*" format.
2. A virtual door plane covering the door opening was drawn which formed the reference marker for passenger quantitative observations. Clock time was recorded every time a passengers' head passed through the virtual plane, defined as a "*time stamp*"[53].
3. The data record included whether the passenger was boarding or alighting.
4. The clock times when the train stopped and departed was also recorded.

The process of "*time stamping*" was done manually through careful frame-by-frame observations and was an extremely tedious and time-consuming task. Observation of the train stop and departure times allowed for the analysis of dwell times and afforded the opportunity to study the extent to which B&A volumes influenced dwell times. A sample sheet of the B&A datasheet is included in Appendix H.

During the data collection, it was found that standing passengers at the door would, more as a result of the alighting pressure than courtesy, briefly alight onto the platform to allow the greater alighting mass to disembark. The same person/s would then board the train again. This was defined as "*courtesy alighting*" and was included in the calculation of the overall boarding and alighting rates.

A total sample of 198 B&A observations were recorded, contributing to a total of 7,426 individual "*time stamped*" observations. Most of the observations were recorded during the AM peak period at Bonteheuwel Station. Table 3.13 shows the breakdown of the B&A dataset per station and period.

Table 3.13: Details of the Boarding and Alighting sample set

Station	**AM Peak Sample**	**PM Peak Sample**	**Total Sample**
Bonteheuwel	137	38	175
Maitland	23	0	23
Overall	160	38	198

The data checking process revealed that 13 data samples needed to be omitted from the Bontehuewel Station sample for faulty door operation and a further two data samples needed to be deleted from the Maitland Station sample set, leaving a total dataset sample of 183.

Unfortunately, it was neither practical nor possible to observe the corresponding on-board passenger occupancies. Within the resource and time constraints of this study, this was not possible. Where it was found that coaches were over-capacity, visually affecting the boarding process, this was excluded from the data analysis.

4. ANALYSIS OF PEDESTRIAN EMPIRICAL DATA

This chapter describes the results of the observed empirical data; firstly, how the observed walking speeds are distributed for each facility type followed by how certain (univariate) situational scenarios affect this distribution. This is followed by an in-depth discussion on the development of the macroscopic fundamental relationships and how various flow ratios impact on flow rates and walking speeds. The results of the boarding and alighting observations are then presented concluding with an overall summary discussion of the results.

Readers are to note that whilst a comprehensive analysis of the empirical data has been presented in this Chapter, that only a portion of the results was required for the calibration of the SP-model. The author however believes that it is of great benefit to industry to document all the results investigated, in a way that is useful towards the calibration of more detailed microscopic models, particularly within the South African context.

4.1 Introduction

The tracking dataset comprises the travel times of the pedestrians and the corresponding flows, speeds and densities within the measurement areas observed at each of the surveyed walking facilities. The unit of measure for the pedestrian flow rate (*q*) for stairways, skywalks, and platforms is the number of pedestrians per meter width per time interval (i.e. represented as either pax/m/min or pax/m/s). For the density parameter (*k*), the unit of measure is the number of pedestrians per square meter (pax/m^2) and for speed (*u*), it is measured in m/s.

From the literature review presented in Chapter 2, many researchers have provided the results of their surveys or observations conducted on pedestrian measurements without qualifying the density environments within which the measurements were observed. Before presenting the empirical results undertaken in this research, it is important to highlight that the fundamental relationships of flow, speed and density are affected by a multitude of factors (e.g. environment, pedestrian type and purpose, time of day, etc.) and so each measurement reported in the following sections has been qualified with these associated influencing factors.

Section 4.2 begins by providing the histogram of observed walking speeds for all the facilities observed over the full range of densities followed by the situational effects on these speeds in Section 4.3. The situational effects consider aspects such as gender, person size, baggage etc. on overall walking speeds. Section 4.4 provides the development of the fundamental flow rate (*q*), speed (*u*) and density (*k*) relationships for the skywalk and staircases whilst Section 4.5 provides quantitative detail of the boarding and alighting observations before summarising the most important aspects of the empirical observations in Section 4.6.

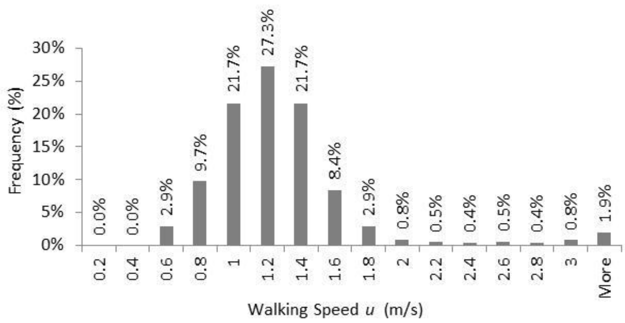
4.2 Distribution of Observed Walking Speeds

4.2.1 Platforms

The average walking speed ($\bar{u}$) of pedestrians in the platform dataset sample (*n* = 2,783) for the entire range of observed densities calculates to 1.19 m/s. The histogram of observed walking speeds is indicated in Figure 4.1. The 1.19 m/s average platform walking speed is lower than the range reported in previous platform walking speed studies of between 1.24 m/s and 1.27 m/s reported by Lam and Cheung (2000) referred to in Subsection 2.3.7. This is however attributable to the fact that the data presented in this subsection includes all data points for all movement types including alighting passengers, boarding passengers and passengers arriving at the platform. Arguably, the walking speeds of those waiting for trains would reduce the average speed considerably.

The effect of platform movement type on walking speeds is demonstrated by the observations made by Daamen and Hoogendoorn (2004) who found average alighting pedestrian walking speeds to be 1.35 m/s compared to the average walking speeds of boarding pedestrians, which was only 0.97 m/s. The isolation and effect of these movement type variables on average platform walking speed for the empirical data collected in this study is assessed later in Subsection 4.3.5.

The overall data appears to be normally distributed about the 1.19 m/s mean, with minimum and maximum walking speeds of 0.44 m/s and 5.82 m/s observed respectively with a standard deviation of 0.514 m/s. The highest reported speed values (viz. those above 2.5 m/s) typically came from the few individuals who ran through the measurement area. Note that the data represents the overall data sample including both free-flow and congested conditions. A summary of the platform data, over all densities, is included in Table 4.1.



<u>Summary Statistics:</u>

Sample size: n = 2,783
Mean: 1.19 m/s
Standard deviation: 0.514 m/s
Minimum: 0.44 m/s
Maximum: 5.82 m/s

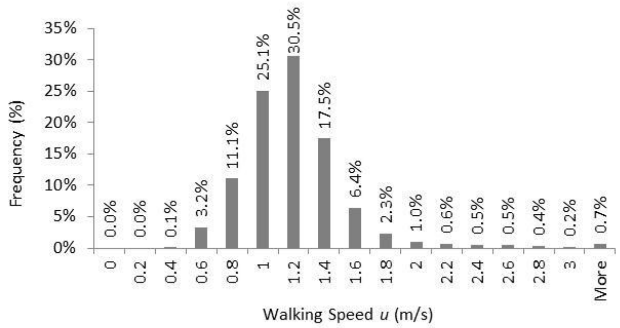
Figure 4.1: Distribution of overall walking speed for platforms (over the full density range)

4.2.2 Skywalks

The average walking speed ($\bar{u}$) of pedestrians for the skywalk dataset sample (*n* = 12,491) is calculated at 1.11 m/s for the entire density range of observations. This average overall speed is amongst the lowest observed when compared to other international free-flow walking speed studies ranging from between 1.08 m/s and 1.60 m/s as reported in Subsection 2.3.7; refer to Figure 2.9.

The average 1.11 m/s walking speed ($\bar{u}$) is however an overall speed for the entire sample dataset and therefore incorporates walking speeds at all densities and cannot be considered a free-flow average speed, since this is typically measured at lower LOS A or LOS B density levels, normally associated with corresponding higher average walking speeds. The comparison of average walking speeds for skywalks observed at the LOS A and LOS B density criteria is described in further detail in Subsection 4.4.2.

The histogram of skywalk walking speeds is indicated in Figure 4.2. The figure shows a skewed distribution, with minimum and maximum walking speeds of 0.25 m/s and 5.37 m/s recorded respectively with a standard deviation of 0.384 m/s. Again, the highest reported walking speed values (viz. those above 2.5 m/s) typically came from the few individuals who ran through the measurement area. A summary of the skywalk data, over all densities, is included in Table 4.1.



Summary Statistics:

Sample size: n = 12,491
Mean: 1.11 m/s
Standard deviation: 0.384 m/s
Minimum: 0.25 m/s
Maximum: 5.37 m/s

Figure 4.2: Distribution of overall walking speed for skywalks (over the full density range)

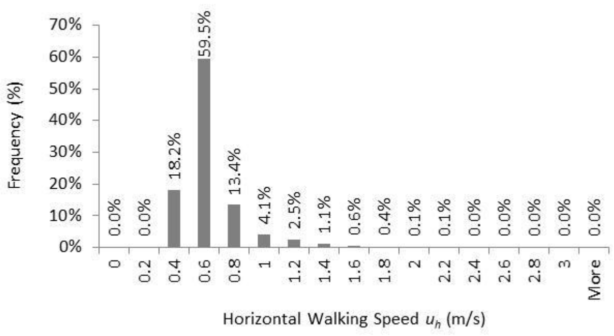
4.2.3 Stairs

The average horizontal walking speed ($\bar{u}_h$) of pedestrians for the stair dataset sample (n = 9,988) as a whole i.e. for both the ascending and descending directions combined is calculated at 0.55 m/s for the entire density range of observations. This combined average horizontal walking speed tends to lie towards the bottom of the range of free-flow walking speeds of other international studies reported in Subsection 2.3.8.

Incidentally, the average horizontal walking speed determined for stairs in this study corresponds exactly to the average ascending and descending horizontal walking speed as observed elsewhere in South Africa by van As and Joubert (1993). More recent observations undertaken by Kretz *et al.* (2008) indicate horizontal walking speeds much lower than that observed in this study viz. between 0.36 m/s and 0.42 m/s, depending on the density situation.

Again, the 0.55 m/s average walking speed reported in this study is an overall horizontal speed for the entire sample set and incorporates speeds observed over all density ranges and cannot therefore be considered as average free-flow speed, since this is typically measured at lower LOS A or LOS B densities, which will be described in further detail in Subsection 4.4.2.

The histogram of horizontal stair walking speeds is indicated in Figure 4.3. Minimum and maximum speeds of 0.01 m/s and 2.175 m/s respectively are shown with a standard deviation of 0.212 m/s calculated for the data. The lower reported speed values (namely, those below 0.1 m/s) typically came from the few pedestrians who were tarrying and who briefly stopped within the measurement area whilst ascending or descending the stairs, but for which their motion dynamic did not qualify them as "*markers*".



Summary Statistics:
Sample size: n = 9,988
Mean: 0.55 m/s
Standard deviation: 0.212 m/s
Minimum: 0.010 m/s
Maximum: 2.175 m/s
Riser: 160 mm
Tread : 300 mm
Slope: 27.89°

Figure 4.3: Distribution of overall horizontal walking speed for stairs (over the full density range)

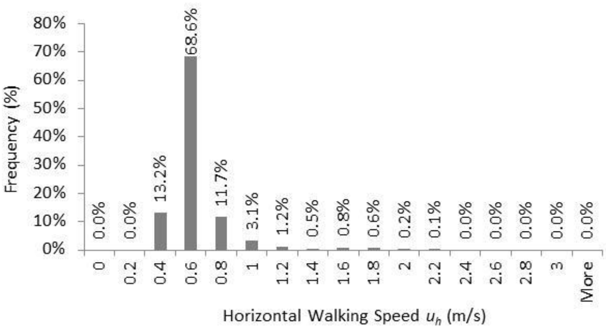
Immediately obvious from the histogram data plotted in Figure 4.3 is the narrow range of walking speed values demonstrated by the small standard deviation not common to the walking speed histogram range observed for the other infrastructure types.

Figure 4.4 (*a.*) and (*b.*) shows the plotted horizontal walking speed histogram data for the ascending and descending directions respectively. The average horizontal walking stair speed ($\bar{u}_h$) for the ascending direction is 0.54 ± 0.206 m/s and 0.55 ± 0.214 m/s for the descending direction respectively. Although seemingly negligible, this difference was nevertheless (just) statistically significant when tested with the Students *t*-test: $t_{up\text{-}down}$ (2.05) > $t_{0.975,\ 9987}$ (1.960) at an α = 5% significance level.

The 0.54 m/s and 0.55 m/s average ascending and descending walking speeds respectively observed in this research is considerably lower than the stair walking speed average of 0.86 m/s (ascending speed) and 0.97 m/s (descending speed) observed by Cheung and Lam (1998) at six stations in Hong Kong referred to in Subsection 2.3.8.

Observations conducted by Daamen and Hoogendoorn (2004) in a Dutch station also revealed higher average horizontal walking speeds of 0.70 m/s and 0.75 m/s for the ascending and descending direction respectively.

Unfortunately, it is not clear from the literature if the observations made by Cheung and Lam (1998) and Daamen and Hoogendoorn (2004) mentioned above were in fact free-flow speeds but other independent stair movement observations made by Pauls in the Society of Fire Protection Engineers *et al.* (1995) reported average descending horizontal free-flow speeds of 0.8 m/s. Other observations by Hankin and Wright (1958) also report free-flow descending horizontal speeds of 0.98 m/s and 0.8 m/s for the ascending direction, closely correlating with the results of Cheung and Lam, suggesting free-flow walking speed averages.



(a.) Ascending condition

Sample size: n = 3,128

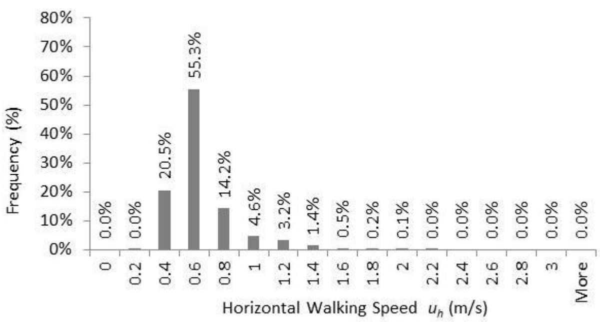
Mean: 0.54 m/s

Standard deviation: 0.206 m/s

Minimum: 0.23 m/s

Maximum: 2.09 m/s

Riser: 160 mm, Tread : 300 mm, Slope: 27.89°



(b.) Descending condition

Sample size: n = 6,860

Mean: 0.55 m/s

Standard deviation: 0.214 m/s

Minimum: 0.01 m/s

Maximum: 2.18 m/s

Riser: 160 mm, Tread : 300 mm, Slope: 27.89°

Figure 4.4: Distribution of overall horz. (*a.*) ascending and (*b.*) descending stair walking speeds (full density range)

The average horizontal stair walking speeds presented in this section have been calculated over the full density range of observations and therefore does not constitute free-flow speed. This distinction and further analysis will be conducted in Subsection 4.4.2. A summary of the staircase data, over all densities, is included in Table 4.1.

Table 4.1: Summary of overall walking speed results per infrastructure type

Infrastructure Type	Walking Speed *u* (m/s)					
	mean	median	SD	minimum	maximum	*n*
Platform	1.19	1.12	0.51	0.44	5.82	2,783
Skywalk	1.11	1.06	0.38	0.25	5.37	12,491
Stairs (Ascending)*	0.54	0.50	0.21	0.23	2.09	3,128
Stairs (Descending)*	0.55	0.50	0.21	0.01	2.18	6,860
Stairs (Overall)*	0.55	0.50	0.21	0.01	2.18	9,988
**Horizontal speed*					Total	35,250

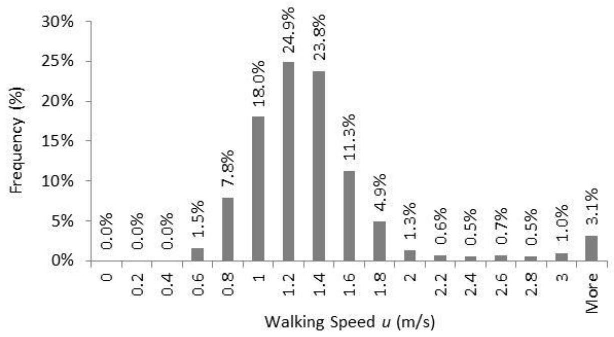
4.3 Situational Effects on Observed Walking Speeds

In the following subsections, the effects of a variety of personal, situational, and environmental factors on pedestrian walking speeds on platforms are explored, in particular the effects of gender, person size, group size, baggage, movement types and the effect of station location and morning and afternoon peaks. It is important to note that the investigation of speed as a function of these individual attributes does not control for other attributes, which can mask important variations. This analysis nevertheless serves as a good indicator of the primary variate trend. A multivariate analysis is necessary to identify underlying relationships but this falls outside the scope of this study and not relevant for model calibration purposes.

4.3.1 Effect of Gender

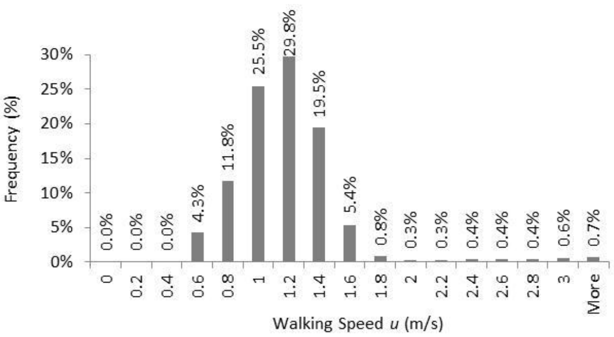
Platforms:

Figure 4.5 (*a.*) and (*b.*) shows the histogram of walking speeds observed for males and females respectively on platforms over the full range of density values. In accordance with several previous studies identified in Subsection 2.3.7, we found that males walked, on average, 15.5% faster than females. The difference between the male average walking speed of 1.29 m/s and the female average walking speed of 1.09 m/s was highly significant when tested with the Students *t*-test: $t_{male\text{-}female}$ (10.55) > $t_{0.975,\ 2782}$ (1.961) at a α = 5% level of significance. Variability was slightly higher amongst males (as indicated by a larger standard deviation), but walking speeds appear to be normally distributed around the mean for both gender groups.



(a.) Males

Summary Statistics:
Sample size: n = 1,431
Mean: 1.29 m/s
Standard deviation: 0.597 m/s
Minimum: 0.44 m/s
Maximum: 5.82 m/s



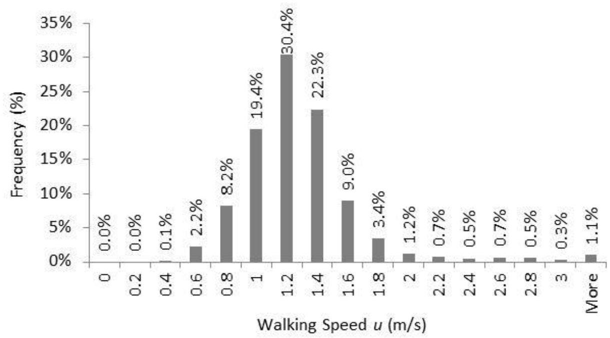
(b.) Females

Summary Statistics:
Sample size: n = 1,352
Mean: 1.09 m/s
Standard deviation: 0.382 m/s
Minimum: 0.44 m/s
Maximum: 4.21 m/s

Figure 4.5: Distribution of (*a.*) male and (*b.*) female walking speeds on platforms (over the full density range)

Skywalks:

Figure 4.6 (*a.*) and (*b.*) shows the histogram of walking speed observed for males and females respectively on skywalks over the full range of density values. As with the platform data, we found that males walked, on average, 15.1% faster than females. The difference between the male average walking speed of 1.19 m/s and the female average walking speed of 1.01 m/s was highly significant when tested with the Students *t*-test: $t_{male\text{-}female}$ (26.36) > $t_{0.975,\ 12490}$ (1.960) at a α = 5% level of significance level. Variability was slightly higher amongst males like the platform dataset, with walking speeds normally distributed around the mean for both gender groups.



(a.) Males

Summary Statistics:

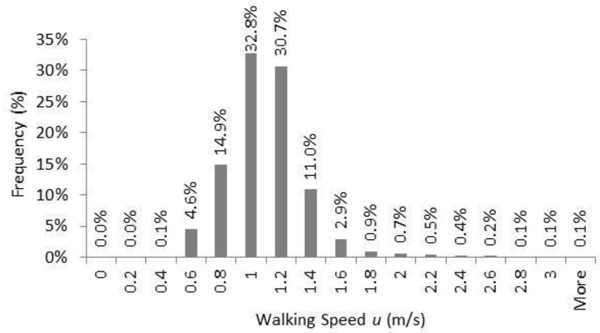
Sample size: n = 7,166

Mean: 1.19 m/s

Standard deviation: 0.426 m/s

Minimum: 0.25 m/s

Maximum: 5.37 m/s



(b.) Females

Summary Statistics:

Sample size: n = 5,325

Mean: 1.01 m/s

Standard deviation: 0.291 m/s

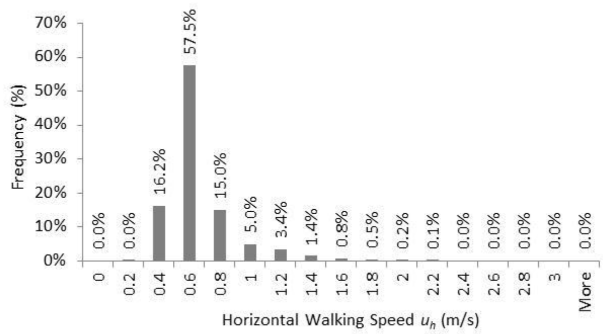
Minimum: 0.29 m/s

Maximum: 3.66 m/s

Figure 4.6: Distribution of (*a.*) male and (*b.*) female walking speeds on skywalks (over the full density range)

Stairs:

Figure 4.7 (*a.*) and (*b.*) shows the histogram of horizontal walking speeds observed for males and females respectively on stairs for both directions over the full range of density values.



(a.) Males

Sample size: n = 6,892

Mean: 0.57 m/s

Standard deviation: 0.234 m/s

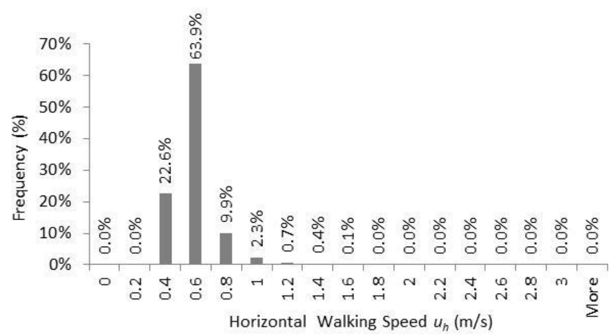
Minimum: 0.01 m/s

Maximum: 2.17 m/s

Riser: 160 mm

Tread : 300 mm

Slope: 27.89^o



(b.) Females

Sample size: n = 3,096

Mean: 0.497 m/s

Standard deviation: 0.140 m/s

Minimum: 0.23 m/s

Maximum: 1.50 m/s

Riser: 160 mm

Tread : 300 mm

Slope: 27.89^o

Figure 4.7: Distribution of (*a.*) male and (*b.*) female horiz. stair walking speeds (over the full density range)

As with the platform and skywalk data and other studies, we again found that males negotiated stairs, on average, 12.8% faster than females. The difference in average horizontal walking speeds between males (0.57 m/s) and females (0.50 m/s) was statistically significant when tested with the Students *t*-test: $t_{male\text{-}female}$ (15.45) > $t_{0.975,\,9987}$ (1.960) at a α = 5% level of significance. Variability was slightly higher amongst males as observed for both the skywalk and platform datasets. Table 4.2 provides a summary list of the overall walking speed results discussed in this subsection.

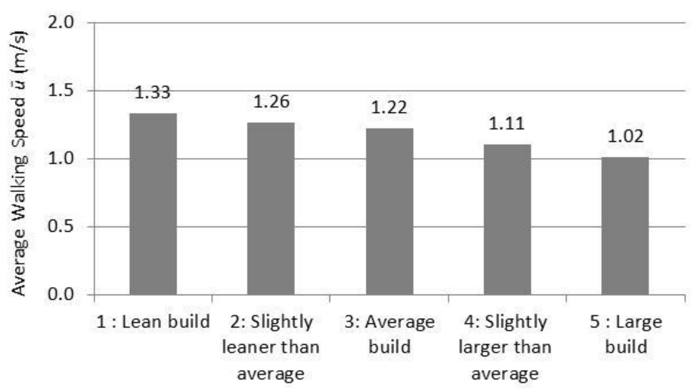
Table 4.2: Summary of overall walking speed results per gender type

Infrastructure Type	Gender	Walking Speed *u* (m/s)					
		mean	median	SD	minimum	maximum	*n*
Platform	Female	1.09	1.05	0.38	0.43	4.20	1,352
	Male	1.29	1.18	0.60	0.44	5.82	1,431
	Overall	1.19	1.12	0.51	0.43	5.82	2,783
Skywalk	Female	1.01	0.99	0.29	0.29	3.66	5,325
	Male	1.19	1.13	0.43	0.25	5.37	7,166
	Overall	1.11	1.06	0.38	0.25	5.37	12,491
Stairs*	Female	0.50	0.48	0.14	0.23	1.50	3,096
	Male	0.57	0.51	0.23	0.01	2.18	6,892
	Overall	0.55	0.50	0.21	0.01	2.18	9,988

**Horizontal walking speed*

4.3.2 Effect of Person Size

It is hypothesised that larger people tend to walk slower than their thinner counterparts. The results of the average platform walking speeds ($\bar{u}$), differentiated by body size, undertaken at the two local stations for both genders combined over the full density range is shown in Figure 4.8. The results show a decreasing trend in average walking speed ($\bar{u}$) for the total population with increasing body size.



Summary Students t-statistics:

$t_{1\text{-}2}$ (1.10) < $t_{0.975,499}$ (1.965); insignificant difference

$t_{1\text{-}3}$ (2.33) > $t_{0.975,1653}$ (1.961); significant difference

$t_{1\text{-}4}$ (5.12) > $t_{0.975,630}$ (1.964); significant difference

$t_{1\text{-}5}$ (6.74) > $t_{0.975,420}$ (1.966); significant difference

$t_{2\text{-}3}$ (1.34) < $t_{0.975,1871}$ (1.961); insignificant difference

$t_{2\text{-}4}$ (4.63) > $t_{0.975,848}$ (1.963); significant difference

$t_{2\text{-}5}$ (6.33) > $t_{0.975,848}$ (1.964); significant difference

$t_{3\text{-}4}$ (4.42) > $t_{0.975,2002}$ (1.961); significant difference

$t_{3\text{-}5}$ (6.32) > $t_{0.975,1792}$ (1.961); significant difference

$t_{4\text{-}5}$ (3.47) > $t_{0.975,769}$ (1.963); significant difference

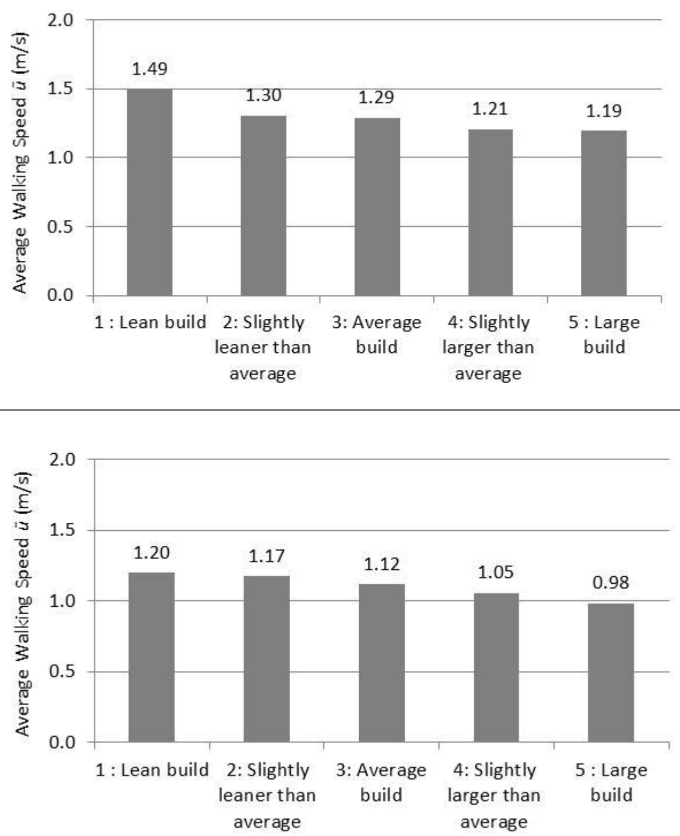
Figure 4.8: Effect of overall person size on average platform walking speeds (over the full density range)

A Students *t*-test shows insignificant differences between the average speeds of body types 1 and 2 and between body types 2 and 3 at the α = 5% level of significance. Body types 4 and 5 show significant differences with all other body type average walking speeds. Table 4.3 provides a summary list of the effects of body size on overall walking speed results.

Table 4.3: Summary of the effect of body size on overall walking speed on platforms

Body Type	Walking Speed *u* (m/s)					
	mean	median	SD	minimum	maximum	n
1: Lean/Small built	1.33	1.17	0.67	0.48	4.21	141
2: Leaner than average	1.26	1.16	0.61	0.44	4.82	359
3: Average Build	1.22	1.15	0.53	0.45	5.82	1,513
4: Slightly Larger than average	1.11	1.06	0.38	0.48	3.69	490
5: Large Built	1.02	1.00	0.30	0.44	3.47	280
					Total	2,783

In South Africa, there is an increased rate of obesity across all economic levels and age groups. According to Kruger *et al.* (2005), 49.3% of black men and 74.6% of black women, who are the predominant users of public transport in this country, are overweight or obese compared to women of mixed ancestry (66%), Asian women (37%) and white women (42.2%). Figure 4.9 shows the results of overall average walking speeds ($\bar{u}$) segregated by both gender and body type for (*a.*) males and (*b.*) females respectively. A comparison of male and female walking speeds shows that declining speeds with increasing body size is common to both genders, but the variation in average walking speed is less elastic for women; in other words, body size has a greater effect on the average walking speed of males than it does for females.



(a.) Males (n = 1,431)

(b.) Females (n = 1,352)

Figure 4.9: Effect of gender specific person size on average platform walking speeds (over the full density range)

Figure 4.10 shows the sample distribution of males and females per body type. As expected, the figure shows that, for both genders, that the person size sample tends to follow a normal distribution about the median (i.e. the average build). The distribution of the female sample however is biased towards the larger frame whilst the distribution of the male sample is conversely biased towards the leaner frame.

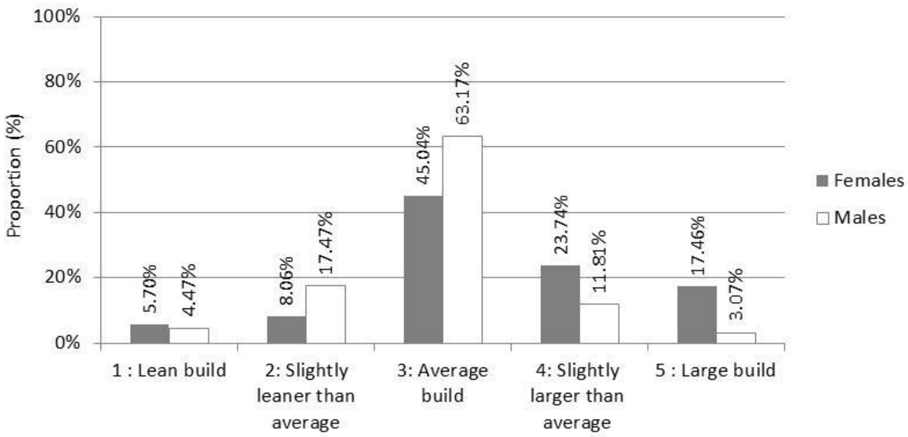


Figure 4.10: Distribution of person size sample according to gender type

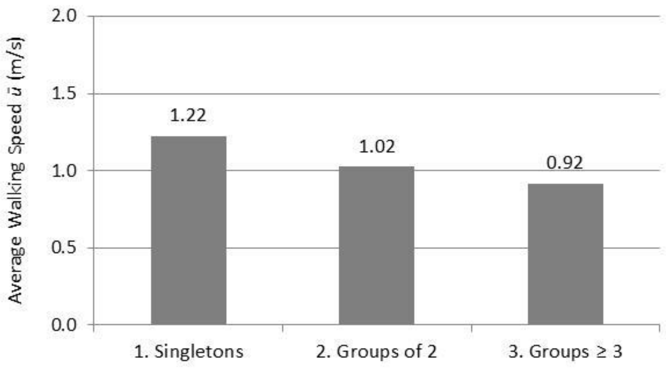
Unlike Kruger *et al.* only 41.1% of females observed in this study were larger than average, but this should be critically viewed in the context of the subjective assessment of body size made during the tracking process as defined in Subsection 3.3.2. Table 4.4 provides a summary list of the effects of body size on overall average walking speed results, segregated by gender type, observed over the full density range.

Table 4.4: Summary effects of body size on gender specific walking speed results on platforms

Body Type	Walking Speed *u* (m/s)					
	Males (*n* = 1,431)			Females (*n* = 1,352)		
	n	mean	*SD*	*n*	mean	*SD*
1: Lean/Small built	64	1.49	0.787	77	1.20	0.523
2: Leaner than average	250	1.30	0.643	109	1.17	0.501
3: Average Build	904	1.29	0.599	609	1.12	0.387
4: Slightly Larger than average	169	1.21	0.434	321	1.05	0.341
5: Large Built	44	1.19	0.406	236	0.98	0.258

4.3.3 Effect of Group Size

The results of group size on average walking speeds ($\bar{u}$) for all genders and density ranges is shown in Figure 4.11. Single pedestrians walked faster, at an average 1.22 m/s when compared to those walking with one or more companions (1.02 m/s and 0.92 m/s respectively).



Summary Students t-statistics:

$t_{1\text{-}2}$ (6.43) < $t_{0.975,2718}$ (1.961); significant difference

$t_{1\text{-}3}$ (4.52) > $t_{0.975,2466}$ (1.961); significant difference

$t_{2\text{-}3}$ (3.13) < $t_{0.975,379}$ (1.966); significant difference

Figure 4.11: Effect of group size on average platform walking speeds (over the full density range)

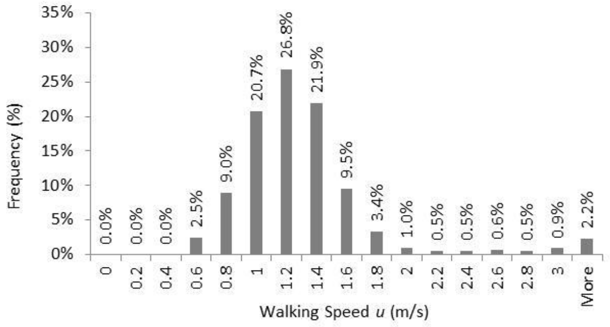
The difference in desired walking speed between singletons and groups of two was highly significant when tested with the Students *t*-test: $t_{1\text{-}2}$ (6.43) > $t_{0.975,\ 2718}$ (1.961) at the α = 5% level of significance. The difference between the average walking speeds of groups of two (1.02 m/s) and groups of three or more persons (0.92 m/s) was also determined to be significant when tested with the Student *t*-test as indicated in Figure 4.11

Figure 4.12 shows the histogram distribution of walking speeds for (*a.*) Singletons, (*b.*) Groups of two and (*c.*) Groups of three or more pedestrians observed on platforms. Table 4.5 tabulates the results and descriptive statistics of the analysis grouped into either individuals or groups or two or more persons.

Table 4.5: Summary of group size walking speeds on platforms isolated by gender type

Group	Gender	Walking Speed *u* (m/s)					
		mean	median	SD	minimum	maximum	*n*
Singles	Female	1.11	1.06	0.40	0.44	4.21	1,097
	Male	1.32	1.20	0.62	0.44	5.82	1,306
Groups (≥ 2)*	Female	1.00	0.99	0.27	0.46	2.86	255
	Male	1.03	1.04	0.21	0.59	1.51	125
** accompanied by either gender*						Total	2,783

The results indicated in Figure 4.11 show a 16.4% drop in average walking speed between singletons and groups of two pedestrians for combined genders. This is more than the 10.5% drop in average walking speed reported by Willis *et al*. (2004) and the 7.8% and 3.2% drop in average walking speed reported by Knoblauch *et al.* (1996) for young and older pedestrians walking alone or in groups respectively.



(a.) Singletons

Summary Statistics:

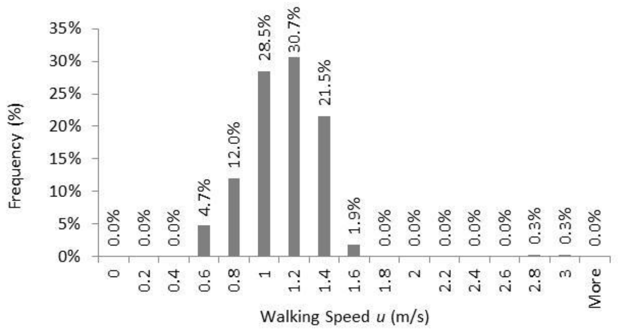
Sample size: n = 2,403

Mean: 1.22 m/s

Standard deviation: 0.54 m/s

Minimum: 0.44 m/s

Maximum: 5.82 m/s



(b.) Groups of 2

Summary Statistics:

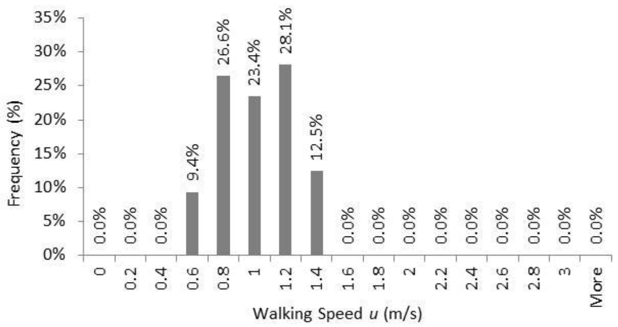
Sample size: n = 316

Mean: 1.02 m/s

Standard deviation: 0.26 m/s

Minimum: 0.46 m/s

Maximum: 2.86 m/s



(c.) Groups ≥ 3

Summary Statistics:

Sample size: n = 64

Mean: 0.92 m/s

Standard deviation: 0.22 m/s

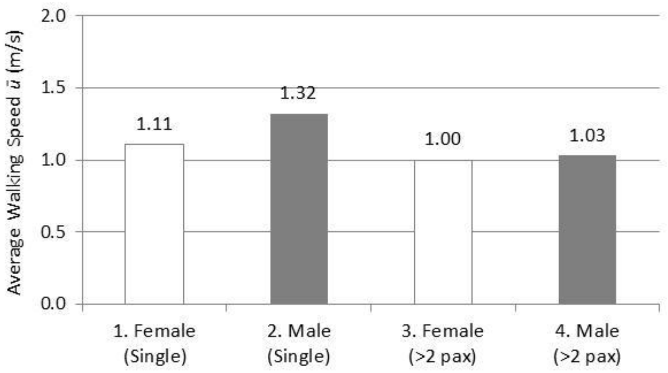
Minimum: 0.51 m/s

Maximum: 1.31 m/s

Figure 4.12: Distribution of platform walking speeds for (*a.*) Singletons (*b.*) Groups of two and (*c.*) Groups ≥ 3

The effect of lower average walking speeds of groups is hypothesised to be influenced in part by gender, as proportionally more females (67.1%) were observed (refer to Table 4.5 in this subsection) to walk in groups of two or more people than males (32.9%). A further analysis was therefore undertaken isolating the average walking speed of groups by gender type.

Figure 4.13 shows the resulting differences in average walking speeds ($\bar{u}$) between the two gender groups as observed on platforms. Note that no differentiation is made for mixed (male-female) gender groups and the assessment involves groups of similar gender only.



Summary Students t-statistics:

$t_{1\text{-}2}$ (9.66) > $t_{0.975,2402}$ (1.961); significant difference

$t_{1\text{-}3}$ (4.18) > $t_{0.975,1351}$ (1.962); significant difference

$t_{1\text{-}4}$ (2.20) > $t_{0.975,1221}$ (1.962); significant difference

$t_{2\text{-}3}$ (8.09) > $t_{0.975,1560}$ (1.961); significant difference

$t_{2\text{-}4}$ (5.20) > $t_{0.975,1430}$ (1.962); significant difference

$t_{3\text{-}4}$ (1.09)< $t_{0.975,379}$ (1.966); insignificant difference

Female: Singletons: n = 1,097 (81.1%);
>2 pax: n = 255 (18.9%)
Males: Singletons: n = 1,306 (91.3%)
>2 pax: n = 125 (8.7%)

Figure 4.13: Effect of group size on average platform walking speeds isolated by gender type

Student's *t*-tests revealed significant differences in average walking speeds between the single groups according to gender, but that the difference was not significant between genders for groups of two or more people. The statistical analysis summary shown in Figure 4.13 confirms that single males walk significantly faster (15.9%) than single females. Conversely male-only groups did not walk significantly faster than female-only groups. In fact the average walking speed of groups of two or more pedestrians for both gender types are remarkably similar. In this instance, the hypothesis that a higher proportion of females in groups leads to lower average walking speeds is therefore false. Rather the general tendency is for groups of either gender to walk slower than their individual counterparts.

To determine if the formation of walking groups was influenced by the work-bound or home-bound trip purpose, the grouping data was segregated according to the AM and PM peak periods respectively assumed to represent the trip types indicated as shown in Table 4.6.

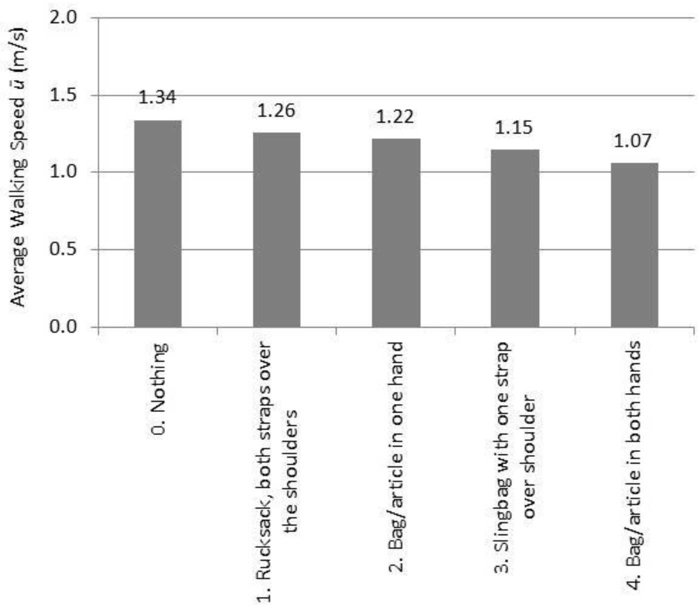
Table 4.6: Group size walking speeds on platforms isolated by peak period

Group	AM Peak	PM Peak	Sample size (*n*)
Singletons	1,575 (87.8%)	828 (83.7%)	2,403
Groups (> 2)	183 (10.2%)	133 (13.5%)	316
Groups (≥ 3)	36 (2.0%)	28 (2.8%)	64
Total	1,794	989	2,783

It was initially assumed, that it would be reasonable to assume that the commuter (work-bound) trip in the morning peak period would be more individualistic, since it originated from home. It would also be considered reasonable to assume that the afternoon (home-bound) trip, originating from a place of employment would afford work colleagues the opportunity to form groups more easily when departing at the end of the workday. Table 4.6 indicates that there is only a marginal support for both the assumptions made above.

4.3.4 Effect of Baggage

The results of carrying baggage on average walking speeds ($\bar{u}$) for all genders and density ranges is shown in Figure 4.14. Over 94% of participants (i.e. 2,627 out of a total sample of 2,783) were classified into the first five baggage carrying categories (viz. 0 to 4). The remainder of pedestrians (n = 156) were associated with a walking aid or a combination of mobility attributes and were excluded from the analysis.



Summary Students t-statistics:

$T_{0\text{-}1}$ (1.49) < $t_{0.975,595}$ (1.964); insignificant difference
$T_{0\text{-}2}$ (2.91) > $t_{0.975,895}$ (1.963); significant difference
$T_{0\text{-}3}$ (6.50) > $t_{0.975,1882}$ (1.961); significant difference
$T_{0\text{-}4}$: T_4 sample too small to consider, n = 18

$T_{1\text{-}2}$ (0.95) < $t_{0.975,725}$ (1.963); insignificant difference
$T_{1\text{-}3}$ (3.27) > $t_{0.975,1712}$ (1.961); significant difference
$T_{1\text{-}4}$: T_4 sample too small to consider, n = 18

$T_{2\text{-}3}$ (2.70) > $t_{0.975,2012}$ (1.961); significant difference
$T_{2\text{-}4}$: T_4 sample too small to consider, n = 18

$T_{3\text{-}4}$: T_4 sample too small to consider, n = 18

Figure 4.14: Effect of carrying baggage on average platform walking speeds (over the full density range)

A Student's *t*-test confirmed that unencumbered pedestrians (viz. Category 0) did not walk significantly faster than Category 1, i.e. those pedestrians that walked wearing rucksacks with both straps engaged. As a result of this insignificance, pedestrians categorised into Category 1 could be classified as unencumbered pedestrians. Unencumbered pedestrians (viz. Category 0) did walk significantly faster on average, than pedestrians in categories 2 and 3 by 8.96% and 14.18% respectively. A Students *t*-test was not conducted against Category 4 due to the low sample rate (n = 18) when compared to the other categories. In such cases, for small sample sizes, the Student's *t*-test result is always significant.

The results of this analysis reveals significant differences in average walking speeds between unencumbered pedestrians and pedestrians carrying baggage, which is contrary to the findings by Fruin (1971); Whyte (1988); Young (1998) and Davis and Braaksma (1988) who reported insignificant differences between these two groups. Our observations however corroborate the more recent findings of Willis *et al.* (2004) who found that pedestrians carrying baggage have significantly slower average walking speeds than pedestrians without baggage.

Willis *et al.* found a 2.67% drop in average speeds between unencumbered pedestrians and pedestrians carrying small bags and a 6.67% drop between unencumbered pedestrians and pedestrians carrying larger bags. The proportional drop cannot however be directly compared to the results of this study due to the highly variable nature of the luggage size and weight possibilities.

Table 4.7 provides a summary list of the effects of baggage size on overall walking speed discussed in this subsection.

Table 4.7: Summary of the effects of carrying baggage on average walking speed on platforms

Category: Baggage Size	Walking Speed *u* (m/s)					
	mean	median	SD	minimum	maximum	*n*
0: Nothing (unencumbered)	1.34	1.18	0.69	0.50	5.82	383
1: Rucksack with both straps engaged	1.26	1.18	0.50	0.54	3.99	213
2: Bag/article carried in one hand	1.22	1.13	0.57	0.46	4.69	513
3: Rucksack with one strap engaged	1.15	1.10	0.45	0.44	5.31	1,500
4: Bag/article carried in both hands	1.07	1.11	0.26	0.68	1.45	18
Carrying other items	1.04	0.93	0.21	0.91	1.29	3
Various combinations of above	Statistics not determined					153
					Total	2,783

To clarify any potential for the cross correlation of factors influencing walking speed, e.g. to discount the possibility that females walk more slowly because they carry more baggage, the encumbrance type criteria was isolated across genders. Figure 4.15 shows the gender sample distribution for the various encumbrance type categories.

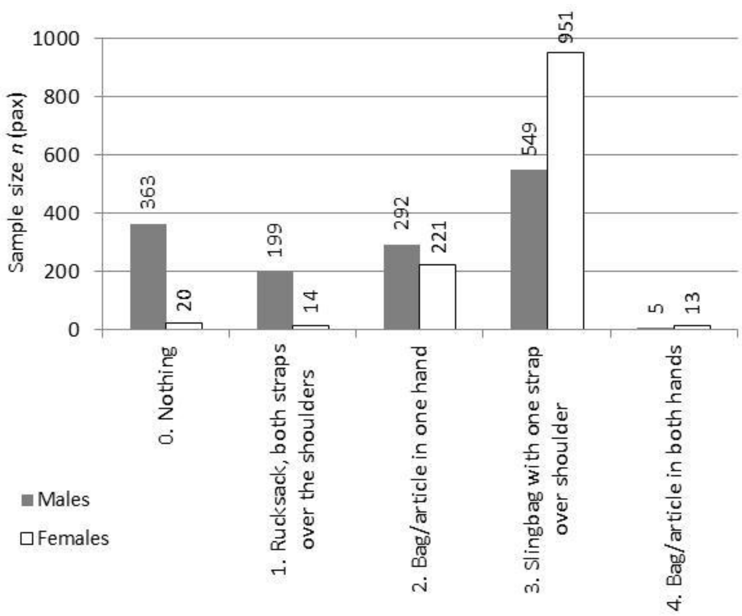


Figure 4.15: Distribution of population across encumbrance type categories per gender

The figure shows that 78% of the female population carries a slingbag or large handbag with one strap over the shoulder (i.e. Category 3) with slightly less than 2% of the female population walking unencumbered. On the contrary, only 39% of the male population walked with a slingbag and 26% of the population walked with no baggage. Few people were observed to carry baggage in both hands viz. Category 4, with less than 1% of the population observed doing so for both genders. It was also observed that 14% of the male population were observed to carry rucksacks (with both straps over the shoulders) compared to their female counterparts, where less than 2% of the population carried rucksacks. Figure 4.16 shows the average walking speeds ($\bar{u}$) on platforms isolated across both genders.

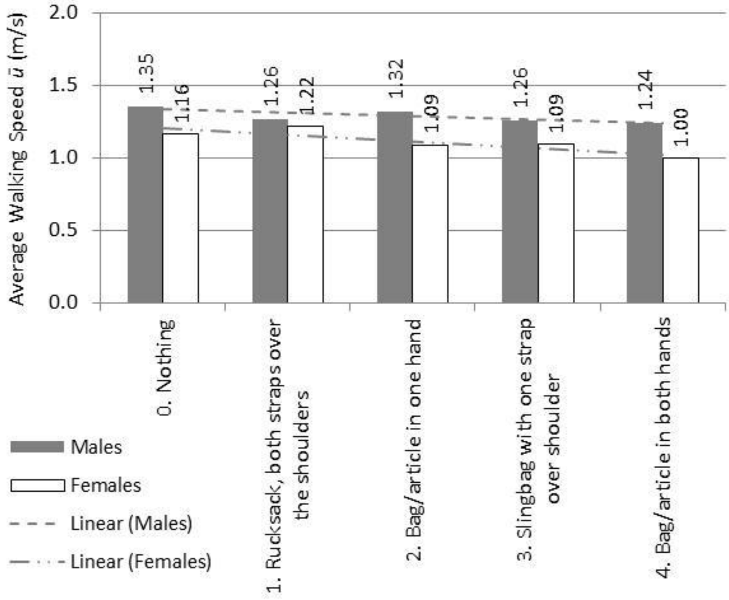


Figure 4.16: Effect of carrying baggage on average platform walking speeds per gender

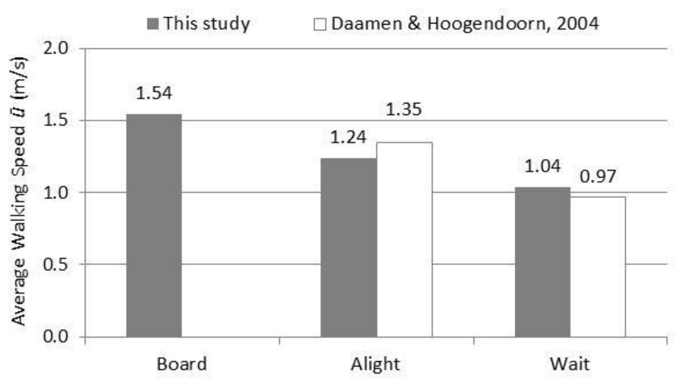
The figure incorporates separate trendlines for both datasets. The figure shows that the trendlines for both genders follow the same decreasing trend for increasing baggage encumbrances (viz. categories from 0 to 4). The figure also shows that despite the higher female sample bias to carry a slingbag/handbag (viz. Category 3), that the average walking speed ($\bar{u}$) for males in this category is 13.5% higher. This is only slightly lower than the overall dataset (observed on platform infrastructure) which indicated a 15.5% difference in walking speeds as determined in Subsection 4.3.1. Table 4.8 tabulates the results of the gender specific assessment together with the sample sizes. The table shows that, despite the population bias of females to carry slingbags or large handbags, the speed differences between males and females across all categories ranged between 3.17% to 19.35%, with males always having the higher speed.

Table 4.8: Summary of the effects of carrying baggage on average walking speed on platforms by gender

Baggage Size	Average Walking Speed $\bar{u}$ (m/s)				
	Males		Females		
	n	$\bar{u}_m$	n	$\bar{u}_f$	$\frac{\bar{u}_m - \bar{u}_f}{\bar{u}_m} x\, 100\%$
Nothing	363	1.35	20	1.16	14.07%
Rucksack with both straps engaged	199	1.26	14	1.22	3.17%
Bag/article carried in 1 hand	292	1.32	221	1.09	17.42%
Slingbag with one strap engaged	549	1.26	951	1.09	13.49%
Bag/article carried in both hands	5	1.24	13	1.00	19.35%
Total	1,408		1,219		

4.3.5 Different Movement Types

The results of the different movement types on platforms, viz. boarding passengers, alighting passengers and passengers arriving on platforms and awaiting trains is presented in this subsection. By way of definition, "*alighting*" passengers are defined as all passengers tracked within the measurement area (MA) walking towards the staircases after alighting from a train. "*Boarding*" passengers are specially defined as all passengers tracked on the platform MA arriving from the staircases onto the platforms *once a train enters the station*. "*Waiting*" passengers are defined similarly to "*boarding*" passengers, but before a train visibly enters the station, who typically need to wait for a train. The results of the average walking speeds ($\bar{u}$) observed for the three movement types are directly compared to the Delft station results of Daamen and Hoogendoorn (2004) as indicated in Figure 4.17.



<u>Summary Students t-statistics:</u>

$T_{board\text{-}alight}$ *(5.53) >* $t_{0.975,1994}$ *(1.961); significant difference*

$T_{board\text{-}wait}$ *(12.28) >* $t_{0.975,894}$ *(1.963); significant difference*

$T_{alight\text{-}wait}$ *(9.64) <* $t_{0.975,2675}$ *(1.961); significant difference*

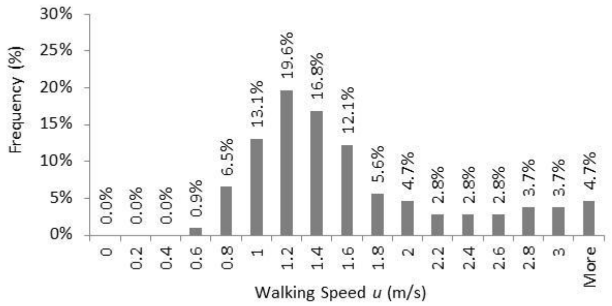
Figure 4.17: Effect of movement type on average platform walking speeds

From Figure 4.17, the boarding passenger group walked significantly faster at an average of 1.54 m/s than the alighting passenger group ($\bar{u}$ = 1.24 m/s) and waiting passenger group ($\bar{u}$ = 1.04 m/s).

The difference in average walking speeds between all three mobility groups was highly significant when tested with the Student's *t*-test: $t_{board\text{-}alight}$ (5.53) > $t_{0.975,\ 1994}$ (1.961) at an α = 5% level of significance. Platform walking speed studies by Daamen and Hoogendoorn (2004) revealed waiting walking speeds of 0.97 m/s and alighting speeds of 1.35 m/s, a difference of 39.2%.

Figure 4.18 shows the distribution of the walking speeds for (*a.*) boarding, (*b.*) alighting and (*c.*) waiting passenger groups respectively. The statistical summary included in the figure shows that our observations corroborate the observations done at Delft station where they found that the average walking speeds of waiting passengers were lower than the average speed of alighting passengers on platforms. Daamen and Hoogendoorn (2004) argue that this is due to the fact that waiting passengers tend to loiter around when waiting for a train whilst alighting passengers have a clear purpose in mind.

In our study, an average waiting walking speed of 1.04 m/s and an average alighting walking speed of 1.24 m/s is calculated, a difference of 19.2%. The average speed comparison between our data and the Dutch data is very similar, with a difference of 8.14% for the alighting data and 7.22% for the waiting data. The high boarding walking speed observed in this study is likely, aside from being left behind, as a result of the very competitive process of boarding overcrowded train coaches with passengers usually competing for standing room only resulting in the need to get to the coach door first.



(a.) Board

<u>Summary Statistics:</u>

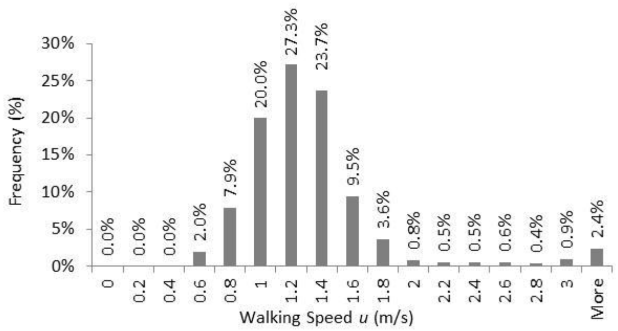
Sample size: n = 107

Mean: 1.54 m/s

Standard deviation: 0.76 m/s

Minimum: 0.56 m/s

Maximum: 4.69 m/s



(b.) Alight

<u>Summary Statistics:</u>

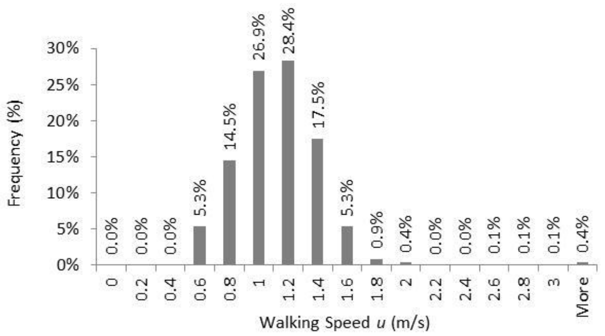
Sample size: n = 1,888

Mean: 1.24 m/s

Standard deviation: 0.54 m/s

Minimum: 0.46 m/s

Maximum: 5.82 m/s



(c.) Wait

<u>Summary Statistics:</u>

Sample size: n = 788

Mean: 1.04 m/s

Standard deviation: 0.32 m/s

Minimum: 0.44 m/s

Maximum: 4.07 m/s

Figure 4.18: Distribution of platform walking speeds for (*a.*) Boarding (*b.*) Alighting and (*c.*) Waiting pax groups

Table 4.9 provides a summary list of the effect of movement type on overall walking speed results discussed in this subsection.

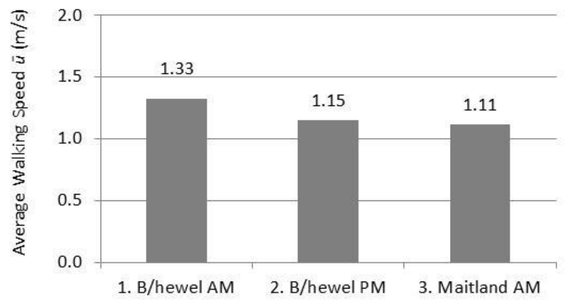
Table 4.9: Summary of the effect of Movement Type on overall walking speed results on platforms

Movement type on platform	Walking Speed *u* (m/s)					
	mean	median	SD	minimum	maximum	*n*
Alighting passenger group	1.24	1.15	0.54	0.46	5.82	1,888
Boarding passenger group	1.54	1.31	0.76	0.56	4.69	107
Waiting passenger group	1.04	1.02	0.32	0.44	4.07	788
					Total	2,783

4.3.6 Effect of Station Location and Peak Time Period

Platforms:

Figure 4.19 shows the measured average walking speeds ($\bar{u}$) at the two station locations during the morning (AM) and afternoon (PM) peaks for the full density range of observations. Unfortunately, no afternoon peak observations were conducted at Maitland station.



Summary Students t-statistics:

T_{1-2} (6.86) > $t_{0.975,1830}$ (1.961); significant difference

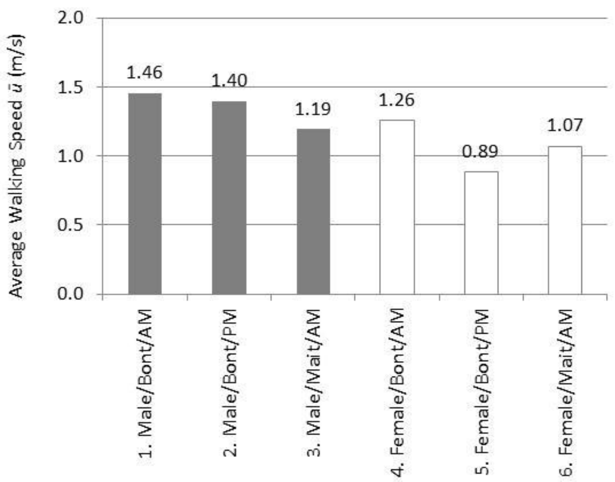
T_{1-3} (9.13) > $t_{0.975,1793}$ (1.961); significant difference

T_{2-3} (1.78) < $t_{0.975,1940}$ (1.961); insignificant difference

Figure 4.19: Effect of location and time period on average platform walking speeds

The Student *t*-test revealed significant differences between morning (AM) and afternoon (PM) peak average walking speeds for Bonteheuwel Station as well significant differences across station locations for the morning peak results at the α = 5% level of significance.

In order to test the significance of location on average walking speed results, person size (=3) , group size (=1), encumbrance (=0) and alighting movement was isolated and statistically tested across locations, gender and period. The results of this analysis is shown in Figure 4.20 below.



Summary Students t-statistics:

Males: ■

T_{1-2} (0.42) < $t_{0.975,129}$ (1.979); insignificant difference

T_{1-3} (3.61) > $t_{0.975,191}$ (1.972); significant difference

Females: □

T_{4-5} (5.83) > $t_{0.975,78}$ (1.991); significant difference

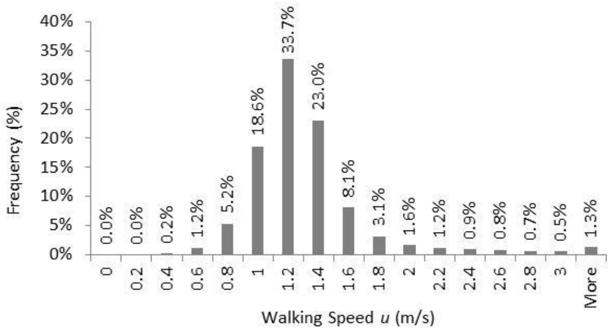
T_{4-6} (3.74) > $t_{0.975,196}$ (1.972); significant difference

Figure 4.20: Effect of location and period on average platform walking speeds isolated by gender

The Student's *t*-test revealed that there are significant differences in average walking speeds at different locations, for the same time period and isolated for both gender types. Interestingly, there is an insignificant difference between average male walking speeds when compared across peak time periods (AM versus PM Peaks viz. scenarios 1 and 2 shown in Figure 4.20) at the same station location. In conclusion, our analysis indicates that location influences walking speeds for all gender types. Time period (AM or PM peak) has a similar significant impact on walking speeds, except for the male gender types where the impact at Bonteheuwel Station was found to be insignificant.

<u>Skywalks:</u>

Figure 4.21 shows the distribution of the average walking speeds ($\bar{u}$) at the two station locations incorporating both the morning (AM) and afternoon (PM) peaks. Figure 4.21 (*a.*) shows the results for Bonteheuwel station and (*b.*) for Maitland Station over the full density range of observations.



(a.) Bonteheuwel Station

<u>Summary Statistics:</u>

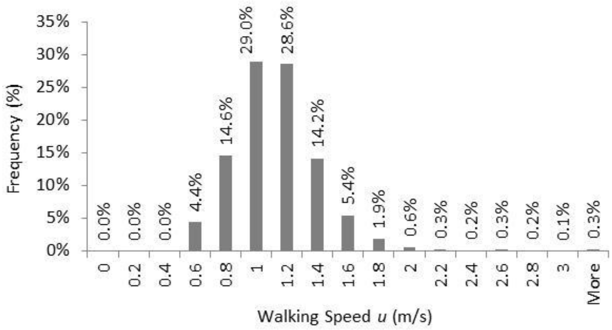
Sample size: n = 4,675

Mean: 1.23 m/s

Standard deviation: 0.44 m/s

Minimum: 0.25 m/s

Maximum: 5.37 m/s



(b.) Maitland Station

<u>Summary Statistics:</u>

Sample size: n = 7,816

Mean: 1.04 m/s

Standard deviation: 0.32 m/s

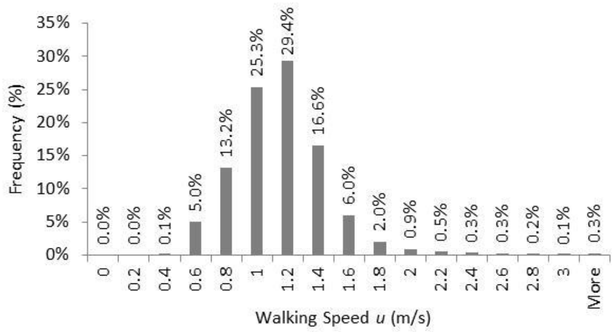
Minimum: 0.37 m/s

Maximum: 4.59 m/s

Figure 4.21: Effect of Station location on skywalk walking speeds (over the full density range)

As with the platform AM peak data, it is observed that the pedestrians on the Bonteheuwel Station skywalks walked, on average, 15.4% faster than those pedestrians observed at the Maitland Station. This difference (1.23 m/s versus 1.04 m/s) was highly significant when tested with the Students *t*-test: $t_{M/land\text{-}B/heuwel}$ (26.74) > $t_{0.975,\ 12490}$ (1.960) at an α = 5% level of significance. Again, walking speeds were normally distributed around the mean for both station locations.

Figure 4.22 shows the distribution of skywalk walking speeds isolated for the morning (*a.*) and afternoon (*b.*) peak periods observed at the two station locations combined. From the results of the peak period analysis, we found that all pedestrians walked, on average, 7.76% faster on skywalks during the PM peak period than the AM peak period. This difference (1.16 m/s versus 1.07 m/s) was highly significant when tested with the Students *t*-test: $t_{AM\ period\text{-}PM\ period}$ (14.00) > $t_{0.975,\ 12490}$ (1.960) at an α = 5% level of significance.



(a.) AM Peak Period

Summary Statistics:

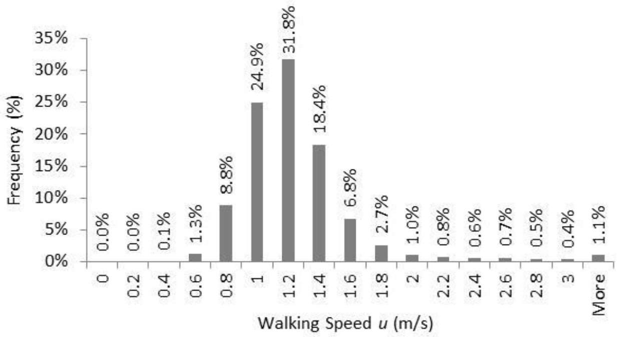
Sample size: n = 6,466

Mean: 1.07 m/s

Standard deviation: 0.34 m/s

Minimum: 0.29 m/s

Maximum: 4.46 m/s



(b.) PM Peak Period

Summary Statistics:

Sample size: n = 6,025

Mean: 1.16 m/s

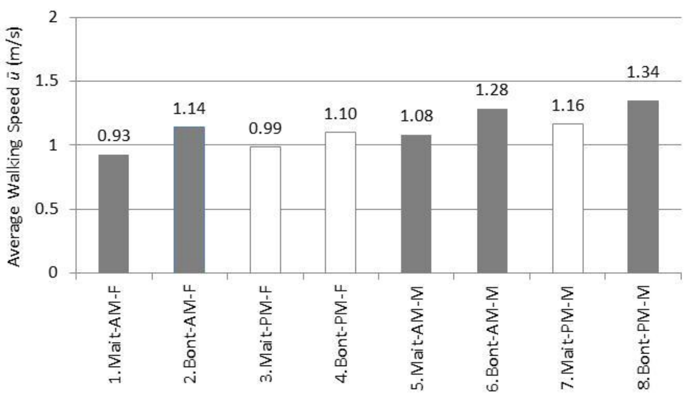
Standard deviation: 0.42 m/s

Minimum: 0.25 m/s

Maximum: 5.12 m/s

Figure 4.22: Distribution of skywalk walking speeds isolated by peak time period

In order to determine the effects of gender, period and station location on average walking speed results, these attributes were isolated and statistically tested. The results over the full density range of observations is shown in Figure 4.23.



Summary Students t-statistics:

AM Peak: ■

$T_{1\text{-}5}$ *(17.73) >* $t_{0.975,4949}$ *(1.960); significant difference*

$T_{2\text{-}6}$ *(7.31) >* $t_{0.975,1515}$ *(1.962); significant difference*

PM Peak: □

$T_{3\text{-}7}$ *(14.20) >* $t_{0.975,2865}$ *(1.961); significant difference*

$T_{4\text{-}8}$ *(14.98) >* $t_{0.975,3158}$ *(1.961); significant difference*

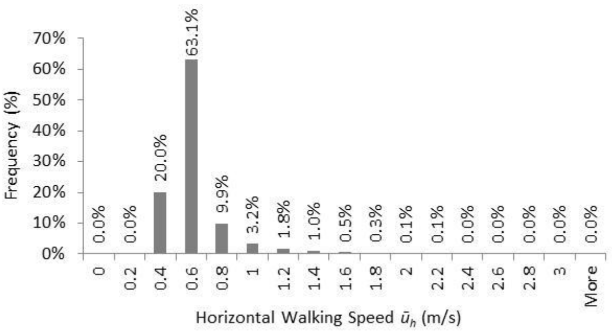
Figure 4.23: Average skywalk walking speeds isolated for location, time period and gender

A Student's *t*-test revealed that there are significant differences in average walking speeds at different locations, for the same peak time period for both gender types. Interestingly, although it has been established that males on average walk faster than females and pedestrians on average walk faster at Bonteheuwel Station than at Maitland Station, Figure 4.23 shows that, during the AM period, males at Maitland station walk slower at 1.08 m/s (viz. Scenario 5) than females walking at Bonteheuwel station at 1.14 m/s (viz. Scenario 2). In conclusion, our surveys confirm that geographic location of stations influences walking speeds for all gender types and that the peak time period (viz. either AM or PM peak) has a similar significant impact on average walking speeds.

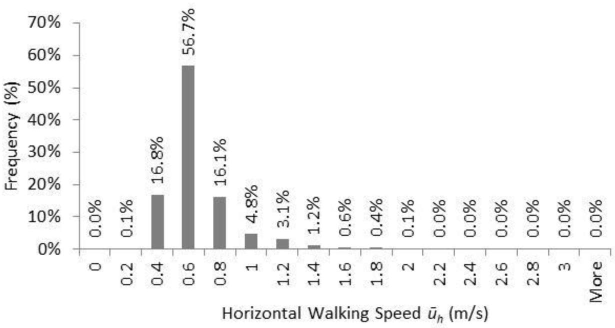
The results of these observations thus do not agree with the observations by Willis *et al.* 2004 who found that walking speeds were similar for the different locations when they isolated the influencing variables. The difference in the operational nature of the two station types, discussed in Subsection 3.1.6, may however be the contributing factor in this instance.

Stairs:

Since staircase pedestrian movement data was only collected at Bonteheuwel Station, a comparison between station locations could not be undertaken. Figure 4.24 shows the distribution of the horizontal walking speeds observed at Bonteheuwel Station for the (*a.*) AM peak period and (*b.*) PM peak periods.



a.) AM Peak Period
Sample size: n = 4,321
Mean: 0.52 m/s
Standard deviation: 0.20 m/s
Minimum: 0.23 m/s
Maximum: 2.18 m/s
Riser: 160 mm
Tread: 300 mm
Slope: 27.89°

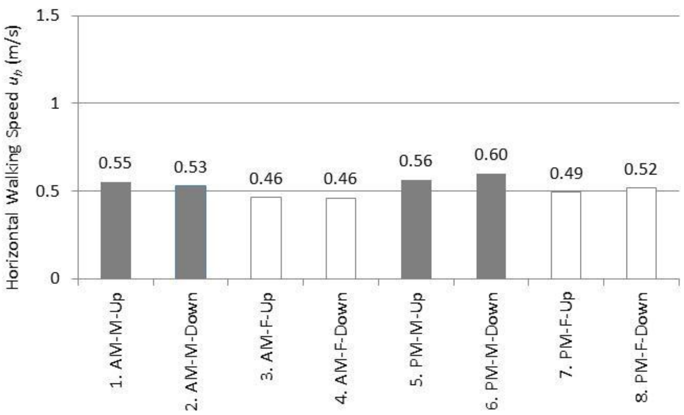


(b.) PM Peak Period
Sample size: n = 5,667
Mean: 0.56 m/s
Standard deviation: 0.22 m/s
Minimum: 0.01 m/s
Maximum: 2.06 m/s
Riser: 160 mm
Tread: 300 mm
Slope: 27.89°

Figure 4.24: Distribution of horizontal walking speeds on stairs isolated by peak time period

From the results of the peak period analysis on staircase pedestrian movement, it is observed that pedestrians walked, on average, 7.70% faster during the PM peak period than the AM peak period, similar to the 7.76% faster observed for the skywalk data. Note that the average speeds indicated in the graph are the average horizontal walking speeds ($\bar{u}_h$) for both ascending and descending directions. The difference between the average AM peak period walking speed of 0.52 m/s versus the PM peak period average walking speed of 0.56 m/s, although only a difference of 7.70%, is significant according to the Students *t*-test: $t_{\text{AM period-PM period}}$ (10.05) > $t_{0.975,\ 9987}$ (1.960) at a α = 5% level of significance.

In order to test the influence of gender, period and direction of motion (viz. ascending or descending) on results, these attributes were isolated and statistically tested as shown in Figure 4.25.



Summary Students t-statistics:

Males: ■

$T_{1\text{-}5}$ (0.89) < $t_{0.975,2333}$ (1.961); insignificant difference

$T_{2\text{-}6}$ (10.36) > $t_{0.975,4557}$ (1.960); significant difference

Females: □

$T_{3\text{-}7}$ (3.97) > $t_{0.975,793}$ (1.963); significant difference

$T_{4\text{-}8}$ (8.54) > $t_{0.975,2301}$ (1.961); significant difference

Sample Sizes:

n_1 = 1,232 *n_5= 1,102*

n_2= 2,020 *n_6= 2,538*

n_3= 380 *n_7= 414*

n_4= 689 *n_8= 1,613*

Figure 4.25: Effect of gender, time period and direction of motion on horizontal staircase walking speeds

The Student's *t*-test revealed that there are both significant and insignificant differences in average horizontal walking speeds on stairs. When the period, gender and direction of movement variables are isolated, the differences in mean walking speed between the ascending (up) and descending (down) movements within genders (viz. scenarios 1 vs. 2 and 3 vs. 4) in the AM peak is not large and in fact was equal for the female gender group (viz. scenarios 3 and 4). Table 4.10 provides a summary list of the station location on the overall walking speed results discussed in this subsection.

Table 4.10: Summary of station location on overall walking speed results per infrastructure type

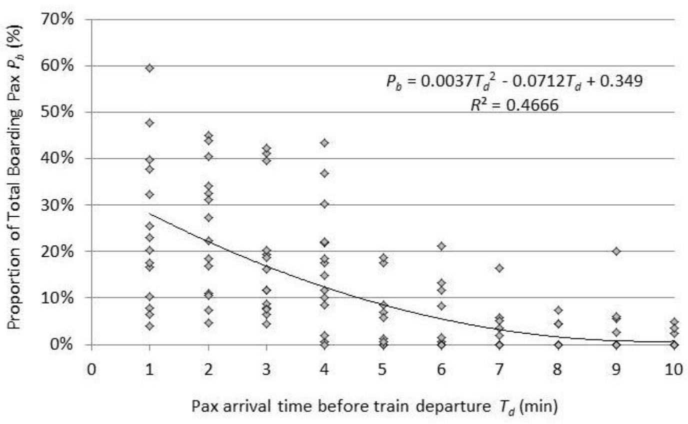
Infrastructure Type	Station	Walking Speed (m/s)					
		mean	median	SD	minimum	maximum	*n*
Platform	Bonteheuwel	1.23	1.16	0.54	0.44	5.82	1,831
	Maitland	1.11	1.03	0.45	0.44	4.52	952
	Overall	1.19	1.12	0.51	0.43	5.82	2,783
Skywalk	Bonteheuwel	1.23	1.14	0.44	0.25	5.37	4,675
	Maitland	1.04	1.01	0.32	0.37	4.59	7,816
	Overall	1.11	1.06	0.38	0.25	5.37	12,491
Stairs*	Bonteheuwel	0.55	0.50	0.21	0.01	2.18	9,988
	Maitland	No stair data observed at this location					
	Overall	0.55	0.50	0.21	0.01	2.18	9,988

**Horizontal walking speed*

4.3.7 Passenger Arrival Rates

For modelling purposes, it was necessary to identify the passenger arrival rates (*PAR*) of the boarding passengers assigned to a particular train. Due to the operational nature of Bonteheuwel Station as a transfer station, the passenger arrival rate (*PAR*) analysis is influenced to a certain extent by transferring passengers from other platforms. Only staircase data could be used to derive *PAR* as the video angle for this dataset allowed for observation of train arrivals and departures. *PAR* was determined from the Bonteheuwel Platform 4 staircase dataset only (refer to platform arrangement in Figure 3.9 (*a.*) in Subsection 3.2.4), as this staircase serves one line thus restricting observations of passengers bound to a single train service only.

Figure 4.26 shows the *PAR* results for each one minute period up to ten minutes prior to train departure. The data is derived from a sample of n = 2,872 arriving passengers intending to board 14 trains during both the AM and PM peak time periods.



Summary statistics:

n = 2,872 pax boarding 14 trains

Maximum boarding load: 467 pax per train

Minimum boarding load: 51 pax per train

Figure 4.26: Passenger arrival rate (*PAR*) observations at Bonteheuwel Station (for both AM and PM peak periods)

On average, 49.6% of all boarding passengers arrive within the last two minutes ($0 \le T_d \le 2$) prior to train arrival, 35.3% arrive between two to four minutes prior to arrival ($2 < T_d \le 4$), 8.3% arrive between four to six minutes prior to train arrival ($4 < T_d \le 6$) and the remaining 6.7% arrive more than six minutes prior to train arrival ($T_d > 6$).

The results shows that, on average, a greater proportion of passengers (i.e. 85% of the total boarding passenger volume) arrive on the platform less than four minutes prior to train arrival ($T_d \le 4$) with fewer passengers arriving (i.e. 15% of the total boarding passenger volume) after the four minute waiting period ($T_d > 4$). The data presented in Figure 4.26 is however indicative only and further work in this field is recommended to be undertaken.

4.4 Pedestrian Flow Parameters and Relationships

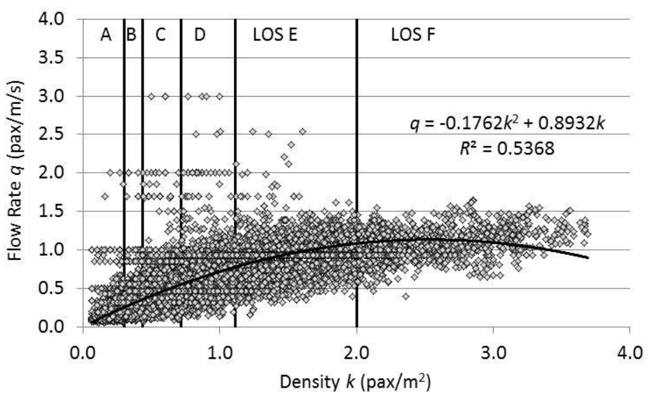
The fundamental relationships of flow rate (q), speed (u) and density (k) observed for the various infrastructure types (except platforms) are discussed in this section. The calculation of the correct platform flow rate parameter is rendered difficult to calculate since pedestrian movement on the platform measurement area is not restricted to a certain vector direction, where pedestrians can enter and exit any of the three sides of the measurement area, which is also significantly affected by cross-flow and standing pedestrians. For this reason, the fundamental relationships for platforms are not analysed. Note that cross-flow activity upstream of the measurement areas may influence the fundamental macroscopic relationship, but the sensitivity of this has not been undertaken in this study.

The pedestrian flow, speed and associated density of each pedestrian are determined and presented in the following subsections for the two infrastructure types (viz. skywalks and stairs), where each data point (represented by a scattered dot in the fundamental relationship diagrams) is based on the time of the reference pedestrian to cover the measurement area length (*MAL*).

4.4.1 Flow-Density Relationship by Facility

<u>Skywalks:</u>

Figure 4.27 shows the *q* versus *k* scatter plot and relationship for skywalks. A general observation of the results is that pedestrian flow rate (*q*) gradually decreases with increasing density (*k*). The density LOS bandwidth values shown in the figure are defined in Appendix C.



<u>Summary Statistics:</u>

Sample n = 12,491

R^2= 0.5368

<u>Density LOS Bandwidths (TCQSM, TRB 1999c):</u>

LOS A < 0.30 pax/m²

0.3 pax/m² < LOS B < 0.43 pax/m²

0.43 pax/m² < LOS C < 0.71 pax/m²

0.71 pax/m² < LOS D < 1.11 pax/m²

1.11 pax/m² < LOS E < 2.00 pax/m²

LOS F > 2.00 pax/m²

Figure 4.27: Flow rate (*q*) versus density (*k*) relationship for skywalks

A second-order polynomial regression equation was fitted to the data points in order to ultimately calibrate the SP-model flow–density function for skywalks. Note the reduced variation in flow rate observations for the LOS F density category. This is attributable to the reduced opportunity for pedestrians to select their free speed at higher densities.

Figure 4.28 provides a comparison with other researched relationships and identifies the "*LOS-mismatch*"[31] for our data. The figure shows the plot of the regression equation for the *q* vs. *k* skywalk relationship identified above and compares this to the relationship proposed by Helbing *et al.* (2007) and to the LOS boundary points using both flow rate criteria (horizontal lines) and density criteria (vertical lines) as recommended by the TCQSM standards (TRB 1999c).

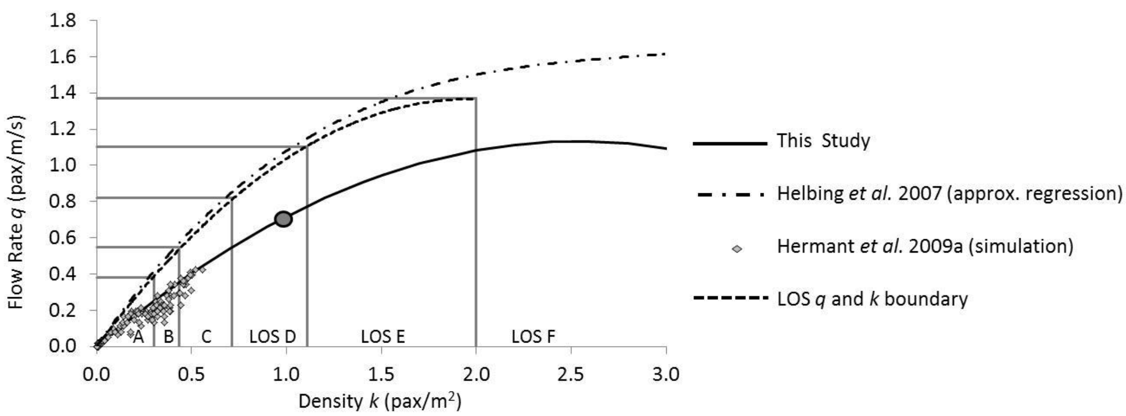


Figure 4.28: Flow rate (*q*) vs. density (*k*) LOS-mismatch for skywalks plotted against data by Helbing *et al.* (2007)

The figure also includes the results of a separate VISSIM microsimulation exercise undertaken by the author, specifically conducted to test the LOS discrepancies for the various assessment criteria during the spatial assessment of Nyanga Station, Cape Town (Hermant *et al.* 2009a). From Figure 4.28, the LOS boundary criteria links closely to the relationship developed by Helbing *et al.* Accordingly, the TCQSM flow rate and density criteria would agree in both respects to the data by Helbing *et al.* 2007 with little mismatch occurring. The situation is entirely different when the LOS boundary criteria are compared against the skywalk q vs. k relationship developed in this research and the figure clearly illustrates the flow rate vs. density "*LOS-mismatch*" phenomena for our data.

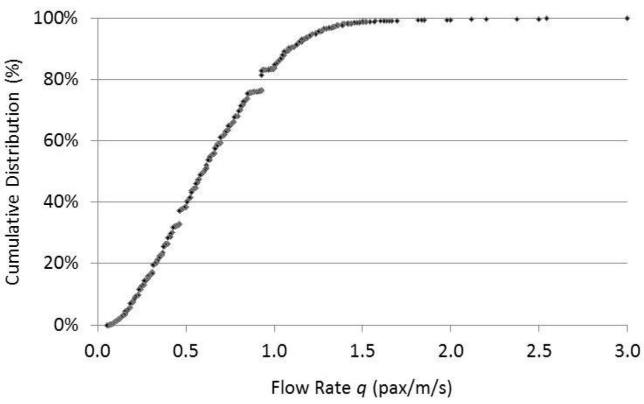
By way of explanation, a density condition of 1.0 pax/m^2 (LOS D) is associated with a flow rate value of 0.7 pax/m/s (LOS C). According to the empirical observations undertaken in this research, the flow rate criteria always gives a better LOS than the density criteria, corroborating the conclusions made by Saif (2009); refer to Subsection 2.2.6. Table 4.11 shows the density and flow rate TCQSM and HCM LOS boundary requirements, stipulated by the Transportation Research Board (TRB 1999c), as well as the observed flow rate guideline (q') according to the relationship determined in this research. From the table, the TCQSM flow rate criteria is overestimated by as much as 36.4%.

Table 4.11: Results of the LOS-mismatch for the skywalk flow-density relationship

LOS	k (pax/m^2)	TCQSM criteria q (pax/m/s)	HCM 2000 criteria q (pax/m/s)	Observed q' (pax/m/s)	% change
A	0.30	0.38	0.23	0.25	-34.2%
B	0.43	0.55	0.35	0.35	-36.4%
C	0.71	0.82	0.55	0.55	-32.9%
D	1.11	1.10	0.82	0.78	-29.1%
E	2.00	1.37	1.00	1.08	-21.2%

Source: TCQSM criteria (TRB 1999c); HCM 2000 criteria (TRB 2000)

This relationship suggests that the flow rate LOS criteria (q) should be reduced appropriately to the local conditions observed (q') prior to applying less conservative TCQSM flow rate LOS criteria for design purposes. From the table, the flow rate observations (q') closely match the HCM 2000 flow rate criteria. From our observations, it would seem that the HCM 2000 flow rate criteria is more appropriate for local conditions. Towards identification of the flow rate capacity (q_c), the cumulative distribution of the skywalk flow rate data points is plotted and presented in Figure 4.29.



Summary Statistics:

Sample n = 12,491

Flow Rate Capacities:

99th percentile: 1.543 pax/m/s

98th percentile: 1.389 pax/m/s

95th percentile: 1.235 pax/m/s

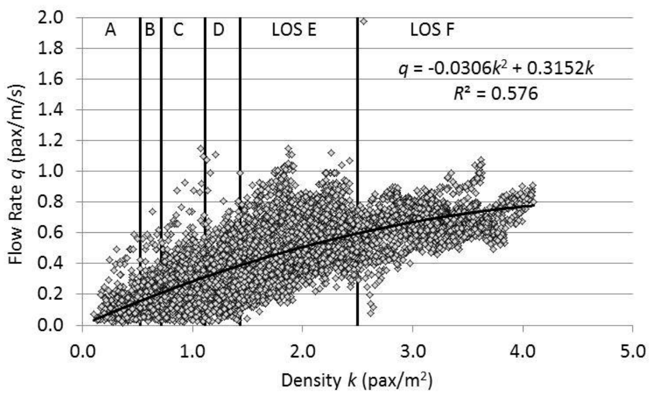
Figure 4.29: Cumulative distribution of the skywalk flow rate (q) data points

Whilst the fitted equation indicated in Figure 4.27 calculates a q_c = 1.13 pax/m/s at a k = 2.53 pax/m^2, the 99th percentile value suggests a q_c value of 1.54 pax/m/s. Further discussion about the calculated capacity is presented in Subsection 4.4.4.

Stairs:

Prior to presenting the results of the empirical data obtained on stairs for this research, it is worthwhile to repeat the statement by Schadschneider *et al.* (2009) made in Subsection 2.3.3 that there is generally no accepted fundamental diagram for the movement on stairs due the impact of stair incline on results.

Figure 4.30 shows the scatter plot showing the q versus k relationship for stairs. A general observation of the results is that pedestrian flow rate gradually decreases with increasing density, as for the skywalk but over a lower flow rate margin. The TCQSM stair density LOS bandwidth values shown in the figure are defined in Appendix C.



Summary Statistics:

Sample n = 8,244

R^2= 0.576

Density LOS Bandwidths (TCQSM, TRB 1999c):

LOS A < 0.53 pax/m^2

0.53 pax/m^2 < LOS B < 0.71 pax/m^2

0.71 pax/m^2 < LOS C < 1.11 pax/m^2

1.11 pax/m^2 < LOS D < 1.43 pax/m^2

1.43 pax/m^2 < LOS E < 2.50 pax/m^2

LOS F > 2.50 pax/m^2

Figure 4.30: Flow rate (*q*) versus density (*k*) relationship for stairs (Overall dataset)

On the basis of the stair scatter plot, a second order polynomial regression equation was fitted to the stair data points as shown in Figure 4.30. Figure 4.31 shows the comparison of the fitted equation against the LOS boundary points designated by the Transportation Research Board (TRB 1999c), shown as horizontal lines for the flow rate criteria and vertical lines for the density criteria.

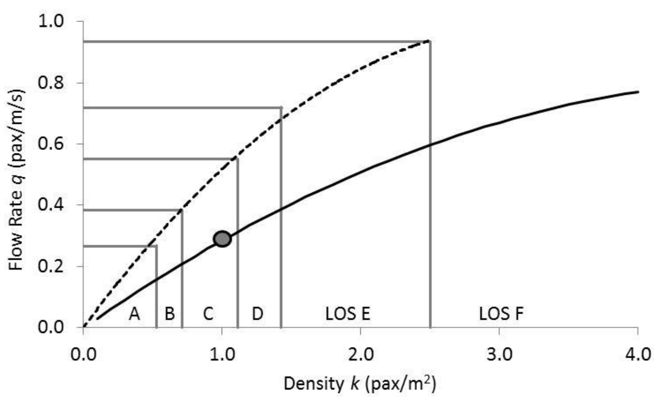


Figure 4.31: Flow rate (*q*) versus density (*k*) relationship LOS-mismatch for stairs

Figure 4.31 again shows a flow rate vs. density "*LOS-mismatch*" phenomena. From the fitted equation, a density condition of 1.0 pax/m^2 (LOS C) is associated with a stair flow rate of 0.3 pax/m/s (LOS B). As with the skywalk data, the flow rate criteria gives a better LOS than the density criteria. Table 4.12 shows the stipulated *k* and *q* LOS boundary requirements stipulated by the TCQSM and HCM 2000 as well as the observed flow rate (*q'*) to suit the density LOS bandwidths. From the table, TCQSM flow rate criteria is overestimated by as much as 45.8%.

Table 4.12: Results of LOS-mismatch for flow-density relationships for stairs

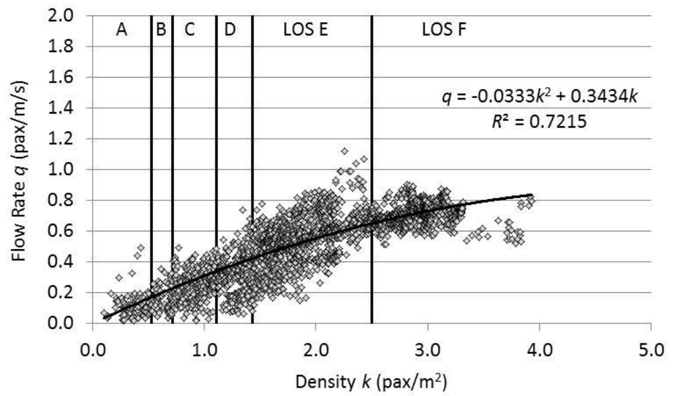
LOS	*k* (pax/m^2)	TCQSM criteria *q* (pax/m/s)	HCM 2000 criteria *q* (pax/m/s)	Observed *q'* (pax/m/s)	% change
A	0.53	0.27	0.27	0.16	-40.7%
B	0.71	0.38	0.33	0.21	-44.7%
C	1.11	0.55	0.43	0.32	-41.8%
D	1.43	0.72	0.60	0.39	-45.8%
E	2.50	0.93	0.82	0.60	-35.5%

Source: TCQSM criteria (TRB 1999c); HCM 2000 criteria (TRB 2000)

As with the skywalk, the relationship suggests that the stair flow rate LOS criteria (*q*) should be reduced appropriately to the local conditions observed (*q'*).

This result highlights the importance of choosing the appropriate LOS criteria. The disconnect phenomena between flow rate and density LOS criteria is termed as the "*LOS mismatch*" in this study. Since the *q* vs. *k* fundamental relationship varies and will always be dependent on a variety of extraneous conditions (i.e. population, culture, temperature, gender mix etc.) the LOS-mismatch problem can be overcome by either developing site specific *q* vs. *k* relationships or by considering only the density criteria for determining the pedestrian spatial LOS values as originally proposed by Fruin (1971a) and Hoogendoorn *et al.* (2007).

Figure 4.32 shows the scatter plot showing the *q* versus *k* relationship for the ascending direction on stairs.



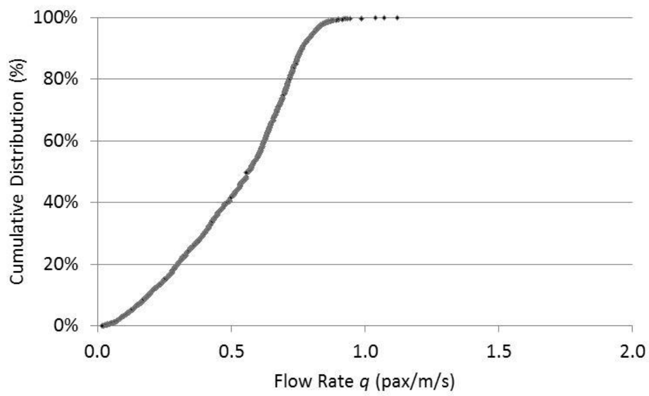
Summary Statistics:
Sample n = 2,655
R^2= 0.722

Density LOS Bandwidths (TCQSM, TRB 1999c):
LOS A < 0.53 pax/m^2
0.53 pax/m^2 < LOS B < 0.71 pax/m^2
0.71 pax/m^2 < LOS C < 1.11 pax/m^2
1.11 pax/m^2 < LOS D < 1.43 pax/m^2
1.43 pax/m^2 < LOS E < 2.50 pax/m^2
LOS F > 2.50 pax/m^2

Figure 4.32: Flow rate (*q*) versus density (*k*) relationship for stairs (ascending direction)

The fitted quadratic equation shows a good correlation coefficient (R^2 = 0.722) but shows an uncharacteristic scatter of results at densities greater than 3.3 pax/m^2. From visual inspection of the data points, it would appear that the maximum ascending flow rate (q_c) is in the order of 0.8 to 0.9 pax/m/s.

Towards the calculation of the flow rate capacity (q_c) for stairs in the ascending direction, the cumulative distribution of the skywalk data points is plotted as presented in Figure 4.33.



Summary Statistics:

Sample n = 2,655

Flow Rate Capacities:

99th percentile: 0.873 pax/m/s

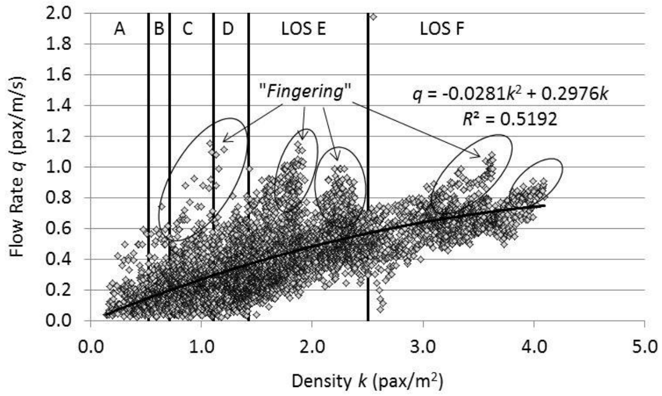
98th percentile: 0.844 pax/m/s

95th percentile: 0.805 pax/m/s

Figure 4.33: Cumulative distribution of flow rate (*q*) for stairs (ascending direction)

Whilst the fitted equation indicated in Figure 4.32 does not to appear to reach a maximum value, the 99th percentile value of the *n* = 2,655 data points suggests a q_c value of 0.873 pax/m/s. Further discussion about the calculated capacity is presented in Subsection 4.4.4.

Figure 4.34 shows the scatter plot showing the *q* versus *k* relationship for the descending direction on stairs.



Summary Statistics:

Sample n = 5,589

R^2 *= 0.519*

Density LOS Bandwidths (TCQSM, TRB 1999c):

LOS A < 0.53 pax/m²

0.53 pax/m² < LOS B < 0.71 pax/m²

0.71 pax/m² < LOS C < 1.11 pax/m²

1.11 pax/m² < LOS D < 1.43 pax/m²

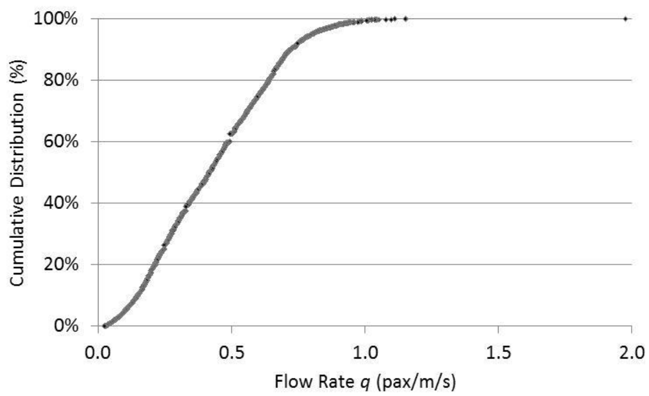
1.43 pax/m² < LOS E < 2.50 pax/m²

LOS F > 2.50 pax/m²

Figure 4.34: Flow rate (*q*) versus density (*k*) relationship for stairs (descending direction)

The fitted quadratic equation for the descending direction shows a worse correlation coefficient (R^2 = 0.519) than the ascending direction possibly due to the "*fingering*" of the data points away from the fitted curve at densities around 1.0, 1.8, 2.2, 3.5 and 4.0 pax/m^2. From visual inspection, the fingering of the data makes it difficult to ascertain a maximum descending flow rate (q_c), but it can be assumed that is should be in the order of 0.8 to 1.0 pax/m/s.

Towards a more accurate calculation of the flow rate capacity (q_c) for stairs in the descending direction, the cumulative distribution of the skywalk data points is plotted as presented in Figure 4.35.



Summary Statistics:
Sample n = 5,589

Flow Rate Capacities:
99th percentile: 0.959 pax/m/s
98th percentile: 0.898 pax/m/s
95th percentile: 0.801 pax/m/s

Figure 4.35: Cumulative distribution of flow rate for stairs (descending direction)

As in the case of the ascending direction, the fitted equation for the descending direction indicated in Figure 4.34 also does not reach a maximum value. In this case, the 99th percentile value of the n = 5,589 data points suggests a q_c value of 0.959 pax/m/s. Further discussion about the calculated capacity is presented in Subsection 4.4.4.

Table 4.13 summarises and tabulates the equation of the curves fitted to the q vs. k data for the various infrastructure types and shows the corresponding R^2 correlation coefficients and flow rate capacities (q_c) based on the 99th percentile of observed values.

Table 4.13: Equations of curves fitted to the observed flow-density relationships by facility

Infrastructure Facility	Equations of Fitted Curves*	R^2	q_c
Skywalk	$q = -0.1762k^2 + 0.8932k$	0.537	1.543 pax/m/s
Stairs	$q = -0.0306k^2 + 0.3152k$	0.576	-
Stairs (Ascending direction)	$q = -0.0333k^2 + 0.3434k$	0.722	0.873 pax/m/s
Stairs (Descending direction)	$q = -0.0281k^2 + 0.2976k$	0.519	0.959 pax/m/s

Note: q = pedestrian flow rate (pax/m/s); q_c = maximum flow rate (pax/m/s); k = density (pax/m^2); R^2 = coefficient of determination
**Whilst other curves were tested to fit the data, the quadratic relationship provided the best R^2 fit*

From the fitted curves of the flow vs. density relationship for the two types of infrastructure facilities, the differences in pedestrian flow characteristics is discussed as follows:

- From the fitted curves to the empirical data, it was found that the maximum flow rate value (q_c) was not achieved for the staircase data despite a significant amount of observations conducted in the LOS F bandwidth. The observations for the skywalk was found to be slightly different where the fitted quadratic curve provided a discernable maximum flow rate value. The reasons proposed for a lack of data past the critical density value (k_c) is the fact that pedestrians will self-organise and simply not allow a more congested density situation to occur and rather wait at the bottom (or top) of the stairs instead of forcing themselves into an already dense LOS F situation, corroborating the observations made by Brocklehurst et al. (2003); refer to Subsection 2.5.3. Also, whilst theoretically the flow rate vs. density curve should decrease in flow rate after the critical density (k_c) is reached, in practice this was not observed corroborating with the observations made by Johnson (1979) and Ye et al. (2008); refer to Subsection 2.3.3.

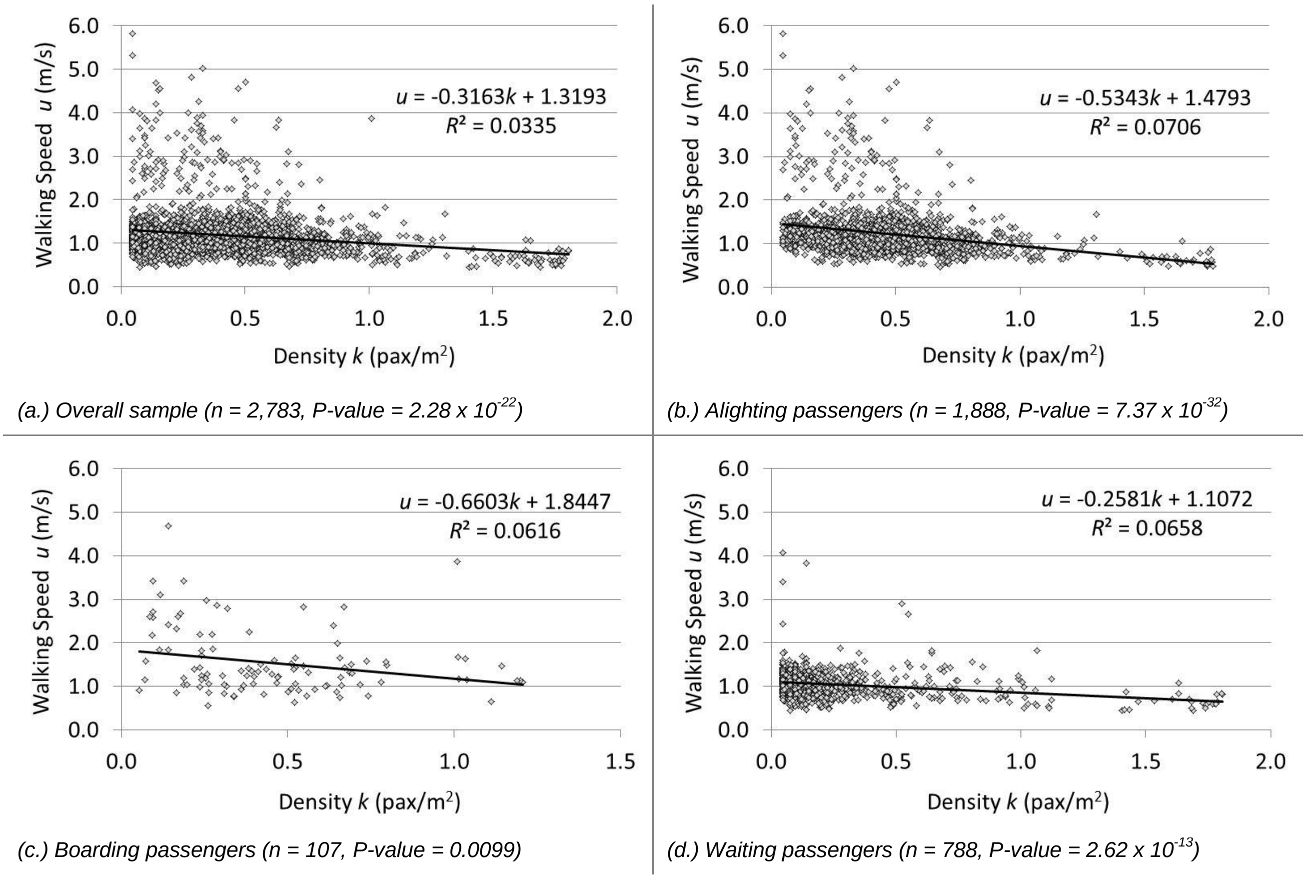
- At the same density, the flow rate capacity (q_c) of the skywalk is higher than that of the staircases, and for staircases, the capacity in the ascending direction is the lowest observed. These results can be explained by the walking behaviour of pedestrians over the various facilities as follows: For ascending or descending stairs, more energy and greater concentration are needed compared with walking on a level surface. The capacity of the staircases is therefore lower than that of the skywalk. The same rules can be applied to compare the flow rate capacity difference between the descending stairway and the ascending stairway. It is similar to the reduction of a vehicle's capacity because of an upward incline, but the capacity reduction for pedestrians on staircases is more striking because the individual personal differences become amplified when the higher requirement of locomotion ability and physical exertion is needed. For example, the old and the very young will feel that climbing stairs is more arduous.

- The change of flow (i.e. slope of the q vs. k curve) is greater on the skywalk than on a stairway when the same increment of density is considered, and the ascending stairway has the minimum flow change for the same density change among the two types of facilities observed. This is as a result of the nature of pedestrian movement on these facilities. On stairs, pedestrians have less flexibility in their mobility than on a level walkway evident by the fact that pedestrians prefer to walk in lanes (viz. directly behind each other) with less bypassing behaviour. As a result, the q vs. k fitted curve is relatively inelastic viz. an increase in density does not significantly change the walking flow rate behaviour on stairs.

4.4.2 Speed-Density Relationship by Facility

Platforms:

Figure 4.36 shows the walking speed (*u*) vs. density (*k*) relationships for (*a.*) the overall platform dataset, (*b.*) for alighting passengers only, (*c.*) for boarding passengers only and (*d.*) for waiting passengers. A general observation of the results is that pedestrian speed decreases with increasing density for all movement types. The decreasing relationship is linear and fitted curves and corresponding R^2 correlation coefficients and *P*-values are indicated in the figures.



(a.) Overall sample (n = 2,783, P-value = 2.28 x 10^{-22})

(b.) Alighting passengers (n = 1,888, P-value = 7.37 x 10^{-32})

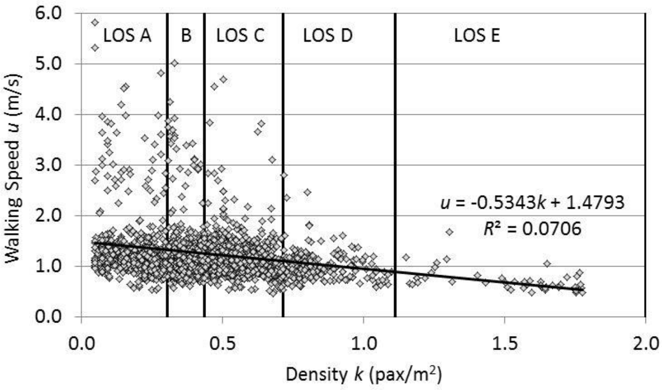
(c.) Boarding passengers (n = 107, P-value = 0.0099)

(d.) Waiting passengers (n = 788, P-value = 2.62 x 10^{-13})

Figure 4.36: Walking speed (*u*) versus density (*k*) plots for various movement types on platforms

Apparent from the figures is the greater variation in flow rate (*q*) data at low densities with typically lower flow rate variance observed for densities greater than 1.0 pax/m^2 (or LOS D) This is attributable to the ability of pedestrians to select their preferred walking speed at free-flow conditions, which they are unable to do at congested conditions.

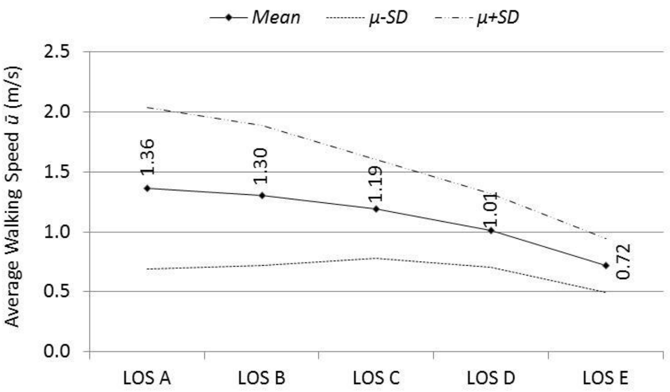
Figure 4.37 shows the walking speed (*u*) vs. density (*k*) relationship for the alighting movement only, together with the summary statistics.



Summary Statistics:
Sample n = 1,888
R^2= 0.0706
P-value = 7.37 x 10^{-32}
t-statistic = -11.966
Density LOS Bandwidths (TCQSM, TRB 1999c):
LOS A < 0.30 pax/m^2
0.3 pax/m^2 < LOS B < 0.43 pax/m^2
0.43 pax/m^2 < LOS C < 0.71 pax/m^2
0.71 pax/m^2 < LOS D < 1.11 pax/m^2
1.11 pax/m^2 < LOS E < 2.00 pax/m^2
LOS F > 2.00 pax/m^2

Figure 4.37: Walking speed (*u*) versus density (*k*) relationship on platforms (alighting movement only)

From the figure, whilst the fitted equation displays a poor correlation coefficient R^2 = 0.07, the linear relationship is nevertheless statistically significant at the 5% level of significance (*P*-value < 5%). Figure 4.38 below shows the gradually decreasing average walking speeds ($\bar{u}$) with poorer levels-of-service. Due to limited platform space, the standard deviation range about the mean (including the sample variance) also reduces significantly. Note that no LOS F conditions for alighting behaviour was observed on the platforms.



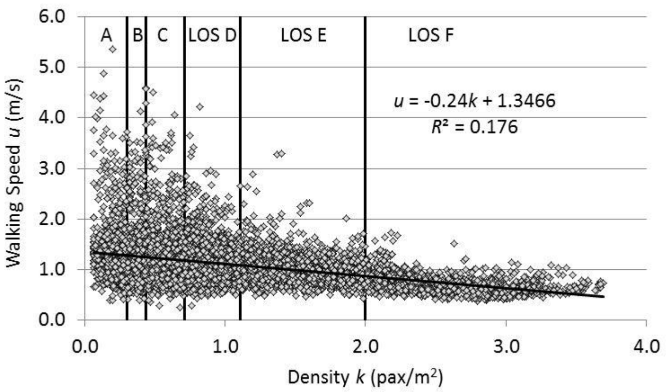
LOS	Sample (*n*)	Mean (*μ*) (m/s)	SD (m/s)	Min (m/s)	Max (m/s)
A	533	1.36	0.67	0.53	5.82
B	425	1.30	0.58	0.57	5.01
C	700	1.19	0.41	0.46	4.69
D	185	1.01	0.31	0.53	2.81
E	45	0.72	0.22	0.48	1.68
F	-	-	-	-	-

Figure 4.38: Variation of average platform walking speeds and variance per density LOS Bandwidths (alighting movement only)

The gradual decrease in standard deviation (SD) with increasing density (poorer LOS) is not a new phenomenon and has been documented by other researchers, including Daamen (2004) referred to in Subsection 2.3.7 and the results of this study confirm this observation.

Skywalks:

Figure 4.39 shows the walking speed (*u*) vs. density (*k*) relationships for the overall skywalk dataset. The decreasing relationship between *u* vs. *k* is linear and a linear equation is fitted to the data.



Summary Statistics:

Sample n = 12,491

R^2= 0.176

P-value = 0

t-statistic = -51.66

Density LOS Bandwidths (TCQSM, TRB 1999c):

LOS A < 0.30 pax/m²

0.3 pax/m² < LOS B < 0.43 pax/m²

0.43 pax/m² < LOS C < 0.71 pax/m²

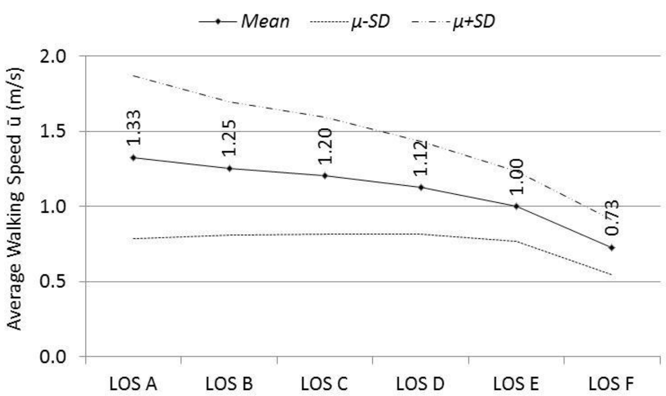
0.71 pax/m² < LOS D < 1.11 pax/m²

1.11 pax/m² < LOS E < 2.00 pax/m²

LOS F > 2.00 pax/m²

Figure 4.39: Walking speed (*u*) versus density (*k*) relationship on skywalks

Although the fitted equation displays a poor correlation coefficient R^2 = 0.176, the linear relationship is nevertheless statistically significant at the 5% level of significance (*P*-value < 5%). Figure 4.40 below shows the gradually decreasing average walking speeds ($\bar{u}$) with poorer levels-of-service and the proportional change and sample variance is almost identical to the platform plot (for alighting movement) across all LOS bands.



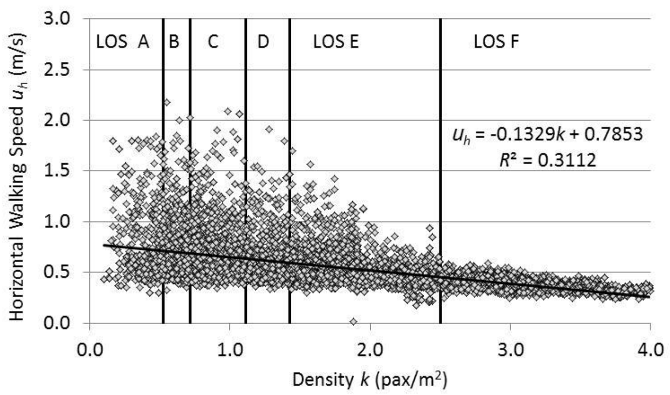
LOS	Sample (*n*)	Mean (*μ*) (m/s)	SD (m/s)	Min (m/s)	Max (m/s)
A	1,176	1.33	0.54	0.39	5.37
B	1,159	1.25	0.44	0.38	4.12
C	3,213	1.20	0.39	0.25	4.58
D	3,092	1.12	0.31	0.29	4.22
E	2,692	1.00	0.23	0.43	3.29
F	1,159	0.73	0.18	0.37	1.73

Figure 4.40: Variation of average skywalk speeds and variance per density LOS Bandwidths

The mean skywalk walking speed of pedestrians within the LOS A bandwidth (*n* = 1,176) is 1.33 m/s which corresponds well to the average speed reported in previous international studies where an average level walkway free-flow speed of 1.36 m/s was reported in Subsection 2.3.7. The mean walking speed of individuals in the LOS B dataset sample (*n* = 1,159) is slightly lower at 1.25 m/s but is within the 1.23 m/s to 1.49 m/s range of free-flow speeds observed in the international literature. The high variability of data points observed at good levels-of-service (i.e. low densities) is as a result of the ability of pedestrians to select their preferred free-flow walking speed.

<u>Stairs:</u>

Figure 4.41 shows the horizontal walking speed (u_h) vs. density (k) relationships for the overall stair dataset for both the ascending and descending direction. The decreasing relationship between u_h vs. k appears linear and a linear equation is fitted to the data.



<u>Summary Statistics:</u>

Sample n = 9,987

R^2= 0.311

P-value = 0

t-statistic = -67.169

<u>Density LOS Bandwidths (TCQSM, TRB 1999c):</u>

LOS A < 0.53 pax/m^2

0.53 pax/m^2 < LOS B < 0.71 pax/m^2

0.71 pax/m^2 < LOS C < 1.11 pax/m^2

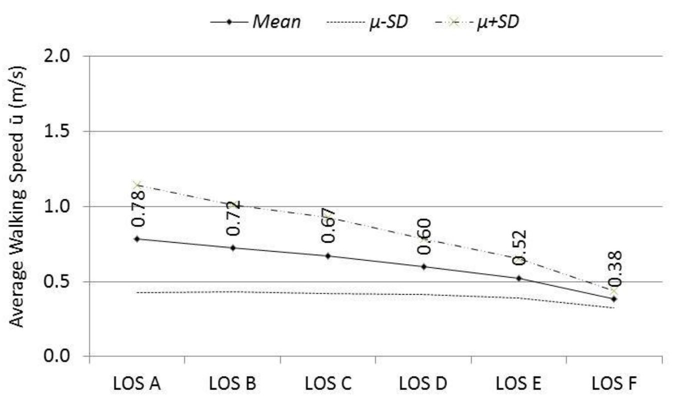
1.11 pax/m^2 < LOS D < 1.43 pax/m^2

1.43 pax/m^2 < LOS E < 2.50 pax/m^2

LOS F > 2.50 pax/m^2

Figure 4.41: Horizontal walking speed (u_h) versus density (k) relationship on stairs (both directions)

Although the fitted linear equation for the stair u_h vs. k relationship is poor viz. a correlation coefficient of R^2 = 0.311, the linear relationship is nevertheless statistically significant at the 5% level of significance (P-value < 5%). Figure 4.42 below shows the gradually decreasing average walking speeds with poorer levels-of-service.



LOS	Sample (n)	Mean (μ) (m/s)	SD (m/s)	Min (m/s)	Max (m/s)
A	447	0.78	0.36	0.30	1.84
B	543	0.72	0.29	0.32	2.18
C	1,445	0.67	0.25	0.34	2.08
D	1,363	0.60	0.18	0.33	1.91
E	3,951	0.52	0.13	0.01	1.69
F	2,239	0.38	0.06	0.23	0.59

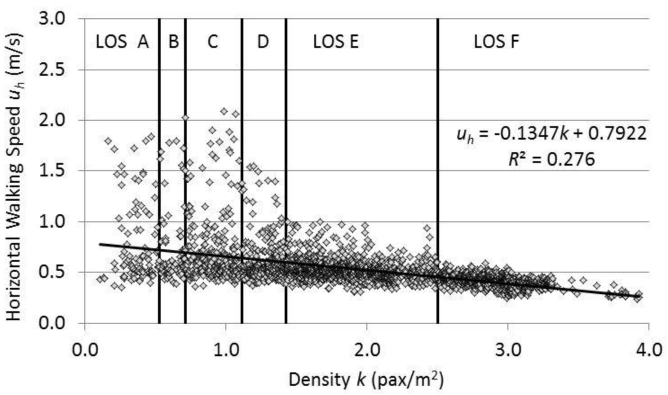
Figure 4.42: Variation of average horizontal stair speeds and variance per density LOS Bandwidths

The mean horizontal walking speed of pedestrians in the LOS A bandwidth (n = 447) is 0.78 m/s and corresponds to the average horizontal stair speeds ($\bar{u}_h$) reported in previous international studies by Lam and Cheung (2000); Daamen and Hoogendoorn (2004) and Berrou *et al.* (2005) reported in Subsection 2.3.7.

From Figure 4.42, it is evident that the sample data follows a much narrower variance than the other infrastructure types. This is due to the fact that the stairs presents a greater mobility challenge and walking speeds are reduced for all densities with very little speed variance at high density levels.

Stairs (Ascending Direction):

Figure 4.43 shows the horizontal walking speed (u_h) vs. density (k) relationships for the overall stair dataset for the ascending direction only. The decreasing relationship between u_h vs. k is linear and a linear equation is fitted to the data.



Summary Statistics:

Sample n = 2,655

R^2= 0.276

P-value = 2.45 x 10^{-188}

t-statistic = -31.804

Density LOS Bandwidths (TCQSM, TRB 1999c):

LOS A < 0.53 pax/m^2

0.53 pax/m^2 < LOS B < 0.71 pax/m^2

0.71 pax/m^2 < LOS C < 1.11 pax/m^2

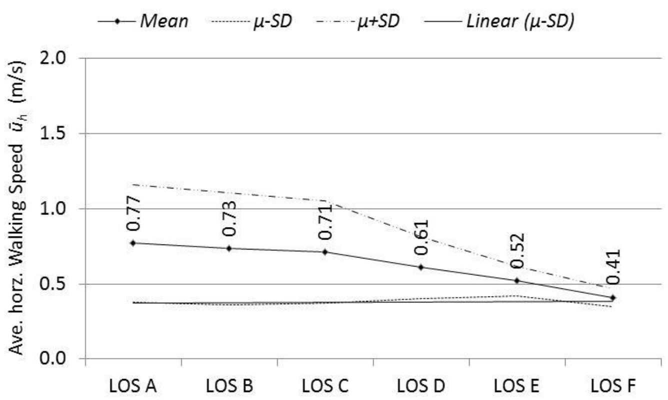
1.11 pax/m^2 < LOS D < 1.43 pax/m^2

1.43 pax/m^2 < LOS E < 2.50 pax/m^2

LOS F > 2.50 pax/m^2

Figure 4.43: Horizontal walking speed (u_h) versus density (k) relationship on stairs (ascending direction)

Again, despite the poor correlation coefficient R^2 = 0.276 for the fitted linear equation for the ascending stair data, the u_h vs. k relationship is nevertheless statistically significant at the 5% level of significance (P-value < 5%). Figure 4.44 below shows the gradually decreasing average horizontal walking speeds with poorer levels-of-service.



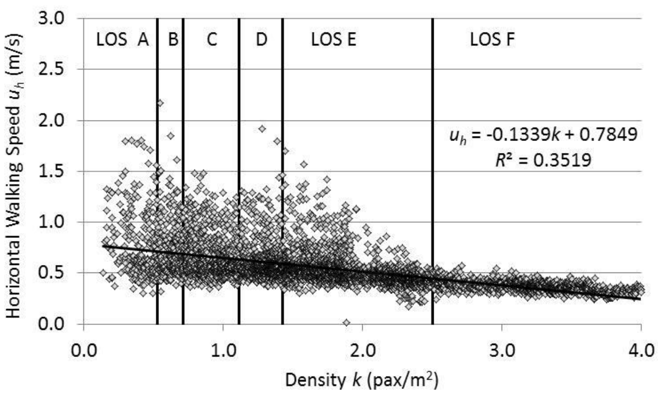
LOS	Sample (n)	Mean (μ) (m/s)	SD (m/s)	Min (m/s)	Max (m/s)
A	95	0.77	0.39	0.35	1.84
B	67	0.73	0.37	0.39	1.80
C	263	0.71	0.34	0.36	2.08
D	288	0.61	0.21	0.37	1.55
E	1,137	0.52	0.10	0.31	1.00
F	805	0.41	0.06	0.23	0.59

Figure 4.44: Variation of average horizontal stair ascending speeds and variance per density LOS Bandwidths

Figure 4.44 shows a greater reduction in the sample variance from LOS C onwards (when compared to the skywalk data; refer to Figure 4.40) to the extent that a standard deviation (SD) of only 0.06 m/s is observed at LOS F.

Stairs (Descending Direction):

Figure 4.45 shows the horizontal walking speed (u_h) vs. density (k) relationships for the overall stair dataset for the descending direction only. The decreasing relationship between u_h vs. k is linear and a linear equation is fitted to the data.



Summary Statistics:

Sample n = 5,589

R^2 = 0.352

P-value = 0.00

t-statistic = -55.075

Density LOS Bandwidths (TCQSM, TRB 1999c):

LOS A < 0.53 pax/m^2

0.53 pax/m^2 < LOS B < 0.71 pax/m^2

0.71 pax/m^2 < LOS C < 1.11 pax/m^2

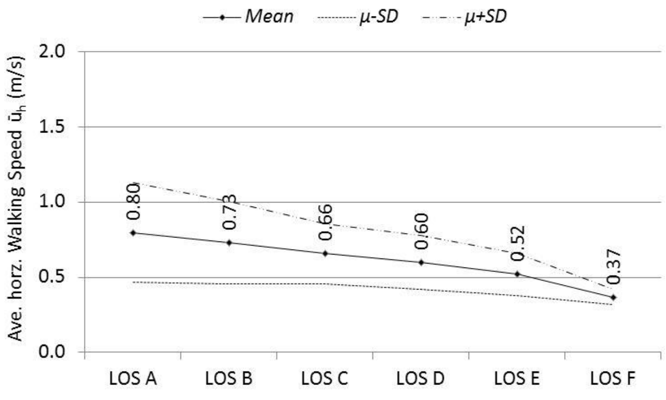
1.11 pax/m^2 < LOS D < 1.43 pax/m^2

1.43 pax/m^2 < LOS E < 2.50 pax/m^2

LOS F > 2.50 pax/m^2

Figure 4.45: Horizontal walking speed (u_h) versus density (k) relationship on stairs (descending direction)

Again, despite the poor correlation coefficient R^2 = 0.276 for the fitted linear equation for the ascending stair data, the u_h vs. k relationship is nevertheless statistically significant at the 5% level of significance (P-value < 5%). Figure 4.44 below shows the gradually decreasing average horizontal walking speeds with poorer levels-of-service.



LOS	Sample (n)	Mean (μ) (m/s)	SD (m/s)	Min (m/s)	Max (m/s)
A	233	0.80	0.33	0.30	1.80
B	265	0.73	0.27	0.32	2.18
C	780	0.66	0.20	0.34	1.48
D	860	0.60	0.17	0.37	1.91
E	2,284	0.52	0.14	0.01	1.69
F	1,167	0.37	0.05	0.24	0.57

Figure 4.46: Variation of average horizontal stair descending speeds and variance per density LOS Bandwidths

The sharp decline in the sample variance is also evident in the descending stair data with a very narrow variance observed in the LOS F density bandwidth, despite the large data sample (n = 1,167) occurring in this bandwidth. Reviewing both the ascending (Figure 4.44) and the descending data (Figure 4.46), it is interesting to note that it is the ascending direction that, apart from the LOS A bandwidth, have the marginally higher average horizontal walking speeds. To test for this significance, an ANOVA analysis was conducted.

The results of an ANOVA analysis conducted to test for difference between the average ascending and descending horizontal stair walking speeds revealed insignificant differences between walking speeds for all the density LOS bandwidths at the α = 5% level of significance with $t_{up,down} = 0.02 < t_{1-\alpha/2,n-k}$ $(t_{0.975,10}) = 2.086$.

Table 4.14 summarises and tabulates the equation of the fitted linear curves to the *u* vs. *k* data for the various infrastructure types and the corresponding R^2 and *P*- values.

Table 4.14: Results of the statistical estimation for speed-density relationships by facility type

Infrastructure Facility	Equations of Fitted Curves*	R^2	*P*-value
Platform (Overall Sample)	$u = -0.3163k + 1.3193$	0.0335	2.28×10^{-22}
Platform (Alighting only)	$u = -0.5343k + 1.4793$	0.0706	7.37×10^{-32}
Platform (Boarding only)	$u = -0.6603k + 1.8447$	0.0616	0.0099
Platform (Waiting only)	$u = -0.2581k + 1.1072$	0.0658	2.62×10^{-13}
Skywalk	$u = -0.24k + 1.3466$	0.176	0.0
Stairs	$u_h = -0.1329k + 0.7853$	0.3112	0.0
Stairs (Ascending direction)	$u_h = -0.1347k + 0.7922$	0.276	2.45×10^{-188}
Stairs (Descending direction)	$u_h = -0.1339k + 0.7849$	0.3519	0.0

Note: u = pedestrian walking speed (m/s); k = density (pax/m^2); R^2 = coefficient of determination; u_h = horizontal walking speed (m/s)

**Whilst other curves were tested to fit the data, the quadratic relationship provided the best R^2 fit*

A summary of the observations made with regard to the walking speed vs. density relationship described in this subsection is discussed as follows:

- In terms of the *u* vs. *k* scatter plots, it was found that walking speed decreases approximately linearly at all densities for all three infrastructure types considered in the analysis.

- Pedestrian walking speeds on stairs decreased with increasing density, but the decreasing trend was found to be less elastic than that of the level skywalk. The reason for this phenomenon is similar to that given in Subsection 4.4.1 viz. because of the special walking behaviour on stairs.

- When the average walking speeds associated with density LOS bandwidths are plotted, then it is evident that there are greater reductions in average walking speed at the LOS E to LOS F bandwidths on the level skywalk than experienced for the staircases where the drop in average walking speed at these levels-of-service is not so pronounced.

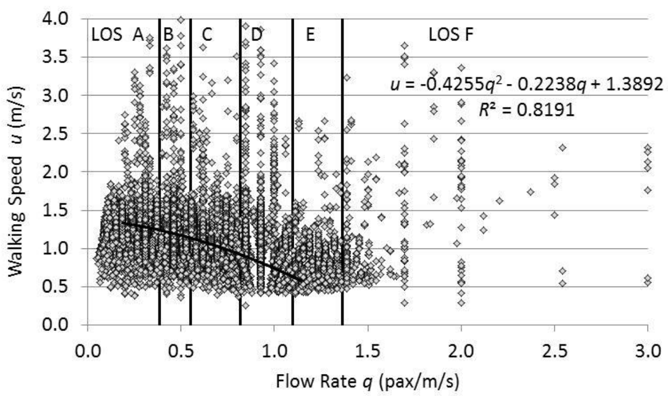
- When densities (*k*) are low, for instance, at LOS D or worse, the variation or distribution of the walking speed observations on level terrain (viz. on the platform and skywalks) is greater than that on staircases. For all infrastructure types, this variation reduces with increasing density (poorer LOS), but this variation reduces significantly at LOS E and F on the platforms and skywalks. This is in accordance with the differences in walking behaviour between staircases and level walkways. At lower densities, walking speed is dominated by personal preference and physical mobility attributes as indicated by the higher speed variance noticed on all the level walking surfaces. On staircases, there is a tendency, particularly at higher densities, for pedestrians to walk in lanes with less bypassing behaviour, causing greater constriction with less opportunity for free-speed selection with the resulting lower variance observed on such infrastructure.

4.4.3 Speed-Flow Rate Relationship by Facility

This subsection describes the speed (*u*) versus flow rate (*q*) relationships observed for the skywalk and stair infrastructure types only. It was not possible to develop a *u* vs. *q* relationship for the platform dataset as a flow rate width cannot be determined for multi-directional flows over the unconfined and open-edged measurement area. Such relationships can however be produced for skywalks and stairs where the width of the measurement area is defined and confined by fixed boundaries.

<u>Skywalk:</u>

Figure 4.47 is a scatter plot of the skywalk data points over all density ranges. A general observation from the scatter plot is that pedestrian walking speeds (*u*) decrease with increasing flow rate (*q*). The scatter plot at first appearance shows great variance with widespread data "*outliers*", but a quadratic equation fitted to the data provides a good correlation coefficient R^2 value of 0.819.



<u>Summary Statistics:</u>

Sample n = 12,491

<u>Density LOS Bandwidths (TCQSM, TRB 1999c):</u>

LOS A < 0.38p/m/sec

0.38 p/m/sec < LOS B < 0.55 p/m/sec

0.55 p/m/sec < LOS C < 0.82 p/m/sec

0.82 p/m/sec < LOS D < 1.10 p/m/sec

1.10 p/m/sec < LOS E < 1.37 p/m/sec

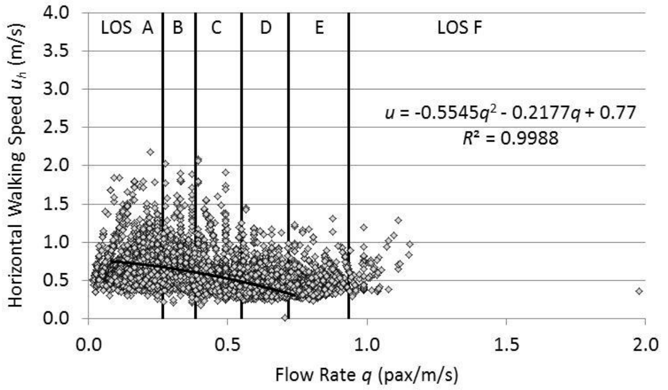
LOS F > 1.37 p/m/sec

Figure 4.47: Walking speed (*u*) versus flow rate (*q*) relationship on skywalks

Most interesting is that whilst the traditional *u* vs. *q* curves would suggest a parabolic curve opening onto the y-axis as reported in Subsection 2.3.2; refer to Figure 2.3 (*c*.), the curve plotted for the skywalk dataset does not adhere to this shape despite the high sample size (*n* = 12,491). Unlike the *q* vs. *k* graphs presented in the previous subsection, the maximum flow rate (q_c) is not evident from the graph.

<u>Stairs:</u>

Figure 4.48 shows the scatter plot of the staircase data over all densities for both the ascending and descending data combined. As with the skywalk *u* vs. *q* plot, the same observation is made where pedestrian speed decreases with increasing flow rate. Immediately noticeable on this scatter plot however, is the close clustering of the data points with very few "outliers". This close clustering of data points permits a R^2 value of 0.999 to be achieved for the fitted quadratic equation indicated in the figure.



Summary Statistics:

Sample n = 8,244

Flow rate LOS Bandwidths (TCQSM, TRB 1999c):

LOS A < 0.27 pax/m/sec

0.27 pax/m/sec < LOS B < 0.38 pax/m/sec

0.38 pax/m/sec < LOS C < 0.55 pax/m/sec

0.55 pax/m/sec < LOS D < 0.72 pax/m/sec

0.72 pax/m/sec < LOS E < 0.93 pax/m/sec

0.93 pax/m/sec < LOS F

Figure 4.48: Horizontal walking speed (u_h) versus flow rate (q) relationship on stairs (overall dataset)

Again, as with the skywalk u vs. q plot, the standard parabolic relationship is not realised in this plot and despite a large sample size (n = 8,244), a maximum flow rate (q_c) can also not be visually determined from this plot. Table 4.15 provides a summary of the quadratic regression equations fitted to the skywalk and stair datasets that best represent the u vs. q relationship.

Table 4.15: Results of the statistical estimation for speed-flow rate relationships by facility

Infrastructure Facility	Equations of Fitted Curves	R^2
Skywalk	$u = -0.4255q^2 - 0.2238q + 1.3892$	0.8191
Stairs (overall dataset)	$u_h = -0.5545q^2 - 0.2177q + 0.77$	0.9988

Note: u = pedestrian walking speed (m/s); q = pedestrian flow (pax/m/sec); R^2 *= coefficient of determination;* u_h *= horizontal walking speed (m/s);*

4.4.4 Comparison of Capacity Flow Rates by Facility

In this subsection, the results of the empirical data is directly compared to the results found in the international literature. A review of the applicability of the local NGS station design guideline document (SARCC 1997) in light of the findings made in the empirical research and resulting MFD relationships is also made in this subsection. For ease of reference, the local NGS standards applicable to various station infrastructure is reproduced (from Subsection 2.1.2) in Table 4.16 below.

Table 4.16: Required LOS standards for South African station design; (Source: SARCC 1997)

Infrastructure Description	TCQSM Criteria	Required AFV (from NGS)	AFV LOS (from TCQSM)	Required APAO (from NGS)	APAO LOS (from TCQSM)
Skywalk	Walkway	0.38 – 0.55 pax/m/s	LOS B	0.30 – 0.43 pax/m^2	LOS B
Corridor	Walkway	0.55 – 0.83 pax/m/s	LOS C	0.43 – 0.71 pax/m^2	LOS C
Stairs (to Platform)	Stairs	0.53 – 0.72 pax/m/s	LOS D	1.08 – 1.54 pax/m^2	LOS D

Skywalk:

The results of the flow rate (q) versus density (k) relationship identified in Subsection 4.4.1 (refer to Figure 4.29) shows a 99th percentile flow rate capacity (q_c) of 1.543 pax/m/s (or 92.6 pax/m/min). This falls within the range of the average 89.19 ± 14.52 pax/m/min capacity for level surfaces determined from the international literature discussed in Subsection 2.3.5. Using the polynomial regression $q = -0.1762k^2 + 0.8932k$ fitted to the skywalk empirical data (shown in Figure 4.27) with $R^2 = 0.5368$, reveals that densities of between 0.47 and 0.72 pax/m^2 are required to comply to the LOS B AFV requirement as indicated in Table 4.16 above.

According to the TCQSM LOS classification (TRB 1999c), this range of density LOS values falls directly within the LOS C bandwidth (refer to Figure 2.19 (*b.*) in Subsection 2.5.1). As recommended by the NGS guidelines for walkways, utilising average design flow values (AFV) of between 0.38 to 0.55 pax/m/s would therefore lead the designer to assume that they are designing to LOS B standards, when in fact the empirical evidence collected in this study suggests that they would in fact be designing to a worse, LOS C standard.

<u>Corridor:</u>

According to Table 4.16, the NGS AFV requirements for the design of corridors is between 0.55 to 0.83 pax/m/s to conform to LOS C specifications. Using the regression equation for the q vs. k relationship defined above yields densities of 0.72 to 1.23 pax/m^2 using these flow rate boundaries. According to the TCQSM LOS classification (TRB 1999c), these values correspond to a LOS D bandwidth and the designer would again be designing to a LOS one lower than expected if using the NGS corridor AFV criteria.

Both the AFV design LOS discrepancies evident for the level walkway and corridor infrastructure types are as a result of the MFD LOS-mismatch phenomena already described in Subsection 4.4.1 and shows the importance of designing to local pedestrian characteristics, as it is evident that each environment has its own unique MFD relationship. This exercise has shown that designing to density (k) LOS standards rather than AFV (q) standards would avoid this dilemma.

<u>Stairs:</u>

From Subsection 4.4.1, the 99th percentile flow rate capacities calculated for the ascending and descending direction, as shown in Figures 4.33 and 4.35, are 0.873 pax/m/s and 0.959 pax/m/s respectively (or 52.38 and 57.54 pax/m/min respectively). The average ascending flow rate capacity for various international studies is calculated at 60.87 ± 8.44 pax/m/min with the descending flow rate capacity calculated at 69.67 ± 11.49 pax/m/min.

According to Table 4.16, the NGS AFV design requirement for stairs is between 0.53 to 0.72 pax/m/s (or 31.8 to 43.2 pax/m/min) to conform to LOS D TCQSM specifications (refer to Figure 2.18 (*a.*) in Subsection 2.5.1). Again, using the regression equation fitted for the q vs. k relationship for stairs (overall dataset) determined in Subsection 4.4.1 (Figure 4.30) yields densities of 2.12 to 3.42 pax/m^2 using these flow rate boundary values. According to the TCQSM LOS definition (refer to Figure 2.18 (*b.*) in Subsection 2.5.1), a density value exceeding 2.50 pax/m^2 corresponds to a LOS F condition and the designer would be designing to, in this instance, an unacceptable LOS, two levels lower than expected if using the AFV criteria.

In conclusion, whilst the AFV and APAO design LOS values proposed in the NGS guidelines match the LOS values as specified in the TCQSM guidelines (TRB 1999c), the relationship does not consider the "*LOS mismatch*" phenomenon that inevitably occurs due to the local dynamic and environment. This exercise has therefore emphasised the importance of using the density (*k)* (or APAO) evaluation criteria over the AFV (*q*) criteria; or to use the AFV (*q*) criteria only when the local pedestrian dynamic relationship has been studied and fully understood. These findings corroborate those made by Saif (2009) and Henson (2000) who both argue that the HCM 2000 level-of-service criteria are not applicable in certain environments due to cultural and ethnic differences.

4.4.5 Comparison of Average Free-Flow Walking Speeds by Facility

In this subsection, the results of the free-flow walking speed empirical data observed as part of this study are compared directly to the results from the international literature.

<u>Level terrain:</u>

The results of the average free-flow speeds identified from the international literature discussed in Subsection 2.3.7 (refer to Figure 2.9) shows an average free-flow walking speed ($\bar{u}_f$) of 1.36 ± 0.13 m/s. The empirical observations conducted on the skywalks in this study revealed an average walking speed of 1.33 ± 0.54 m/s for the LOS A density bandwidth, which corresponds with the results of the international literature for various environments. According to Tregenza (1976), only the LOS A bandwidth can be associated with free-flow conditions and therefore only a comparison with this bandwidth is made in this research. For alighting passengers on platforms, the empirical average free-flow walking speed ($\bar{u}_f$) was calculated to be 1.36 ± 0.67 m/s for the LOS A bandwidth, again closely matching the average free-flow walking speed reported in the literature.

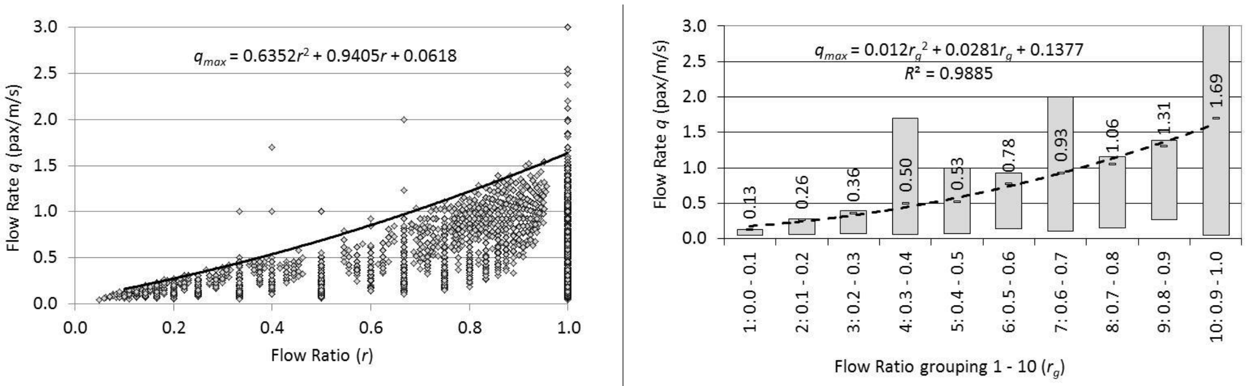
<u>Stairs:</u>

As discussed in Subsection 2.3.8, free-flow walking speed on stairs is influenced by age, physical ability, stair gradient etc. Our empirical research conducted on stairs with risers of 160 mm, treads of 300 mm at a slope of 27.89^o (as presented in Subsection 4.2.3) revealed an average ascending horizontal walking speed of 0.54 ± 0.206 m/s and an average horizontal descending speed of 0.55 ± 0.214 m/s. From Subsection 4.4.2, average free-flow horizontal walking speeds (i.e. all data within the LOS A bandwidth) for the ascending direction was found to be 0.77 ± 0.39 m/s and 0.80 ± 0.33 m/s for the descending direction. The overall results compare favourably with the 0.5 m/s and 0.6 m/s observed by van As and Joubert (1993) for the average horizontal ascending and descending speeds respectively.

4.4.6 Impact of Flow Ratio on Maximum Flow Rates

The flow ratio parameter (*r*) is defined as the pedestrian (pax) volume of one direction divided by the total pedestrian volume in both directions. In this research, flow ratio data was calculated for every pedestrian observed. The relationship between flow ratio (*r*) and pedestrian flow (*q*) and speed (*u*) was explored individually according to the time interval that the target person was within the measurement area for both skywalk and stair infrastructure types.

Figure 4.49 (*a.*) shows the relationship between flow rate (q) and flow ratio (r) observed on the skywalks for all densities. Each data point shown in the graph represents a pedestrian identified by the flow ratio they are in viz. either in the minor ($r < 0.5$) or major flow direction ($r > 0.5$) together with the flow rate (q) observed in their direction. It is important to note that the flow rate indicated in the graph is therefore uni-directional only and does not represent the total bi-directional flow rate. If this were not the case then flow rates observed at flow ratio values (r) between 0.1 and 0.9, between 0.2 and 0.8, and so on, would be identical.



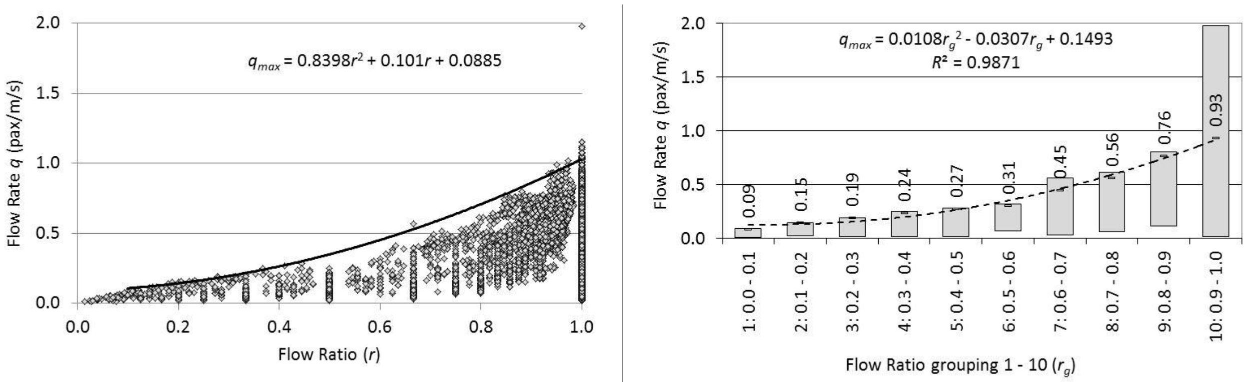
(a.) All data points (Regression based on visual observation)

(b.) Min, 99th percentile and maximum q-values according to r_g

Figure 4.49: Maximum flow rate (q_{max}) versus flow ratio (r) relationship on skywalks (all densities)

Figure 4.49 (*b.*) shows the same plot, but with the flow ratio combined into ten categories or "*groupings*" (r_g). The figure shows the minimum and maximum flow rate range (as a bar graph) as well as the 99th percentile flow rate values for each particular flow rate grouping (r_g). For the purposes of analysis, the maximum flow rate (q_{max}) is assumed to be defined as the 99th percentile flow rate value within a particular flow rate grouping (r_g). A quadratic regression equation, with R^2 = 0.9885 is fitted to the q_{max} versus r_g relationship.

From the graph, we observe a maximum flow rate (q_{max}) drop from 1.69 pax/m/s at r_g = 10 (i.e. r = 0.9 to 1.0) to around 0.13 pax/m/s at r_g = *1* (i.e. r = 0.0 to 0.1), a 92.3% drop in the particular uni-directional flow rate. Similar results were obtained by Blue and Adler (1999) who reported a 90% capacity drop at r = 0.1 on level skywalks. Figure 4.50 (*a.*) and (*b.*) shows the same flow rate versus flow ratio relationship graphs, but for the staircase data.



(a.) All data points (Regression based on visual observation)

(b.) Min, 99th percentile and maximum q-values according to r_g

Figure 4.50: Maximum flow rate (q_{max}) versus flow ratio (r) relationship on stairs (both directions for all densities)

From Figure 4.50 (*b.*), we observe a maximum flow rate (q_{max}) drop from 0.93 pax/m/s at r_g = 10 (i.e. r = 0.9 to 1.0) to around 0.09 pax/m/s at r_g = 1 (i.e. r = 0.0 to 0.1), a 90.3% drop in the particular uni-directional flow rate, a similar percentage drop as reported for the skywalk.

The proposed reason for the significant drop (> 90%) in flow rate capacities (q_{max}) observed for both skywalks and stairs is that pedestrians in the minor flow direction have less freedom or movement choice in order to avoid conflict. The disadvantage of traveling in a minor flow, especially at small flow rates means that it is harder to form a stream and be separated from the major opposing flow. When the minor flow rate increases from a very small percentage to 50%, the chance for pedestrians from a minor flow direction to gain effective capacity by forming streams increases, leading to multiple lane flow, and eventually, to a separated flow condition.

Table 4.17 tabulates the maximum flow rate (q_{max}) values as observed for varying flow ratios for both skywalk and stair infrastructure types for all densities. The approximation of the maximum flow rate (q_{max}) for both skywalks and stairs, plotted in Figure 4.49 (*a.*) and Figure 4.50 (*a.*) respectively, are represented as second-degree polynomial equations as follows:

for skywalks: $q_{max} = 0.6352r^2 + 0.9405r + 0.0618$

for stairs: $q_{max} = 0.8398r^2 + 0.101r + 0.0885$

where q_{max} = maximum flow rate in pax/m/s and r = flow ratio

Table 4.17: Maximum flow rate (q_c) results for different flow ratio values (for all densities)

Skywalk	Flow ratio (r)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Directional max flow (pax/m/min)	9.73	16.52	24.07	32.38	41.45	51.29	61.88	73.24	85.37	98.25
	Bi-directional max flow (pax/m/min)					82.90	83.66	85.95	89.76	95.10	98.25
Stair	Flow ratio (r)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Directional max flow (pax/m/min)	6.42	8.54	11.66	15.80	20.94	27.09	34.24	42.41	51.58	61.76
	Bi-directional max flow (pax/m/min)					41.87	42.88	45.91	50.94	58.00	61.76

Note that the directional maximum flows are uni-directional flow values represented from r = 0.1 to 1.0 and the total bi-directional flow rates are only represented from r = 0.5 to 1.0. This is because the bi-directional flow is calculated as the sum of the uni-directional (minor and major) flows at the respective flow ratios which add to unity (e.g. r = 0.2 and 0.8 or r = 0.3 and 0.7 etc.).

The maximum flow rate (q_{max}) for skywalks and stairs for $0.5 < r < 1$ observed in this research is indicated in Figure 4.51. The relationships are plotted together with the skywalk simulation results by Wang and Liu (2006). In the graph, only the major flow ratio is shown (i.e. $r \geq 0.5$).

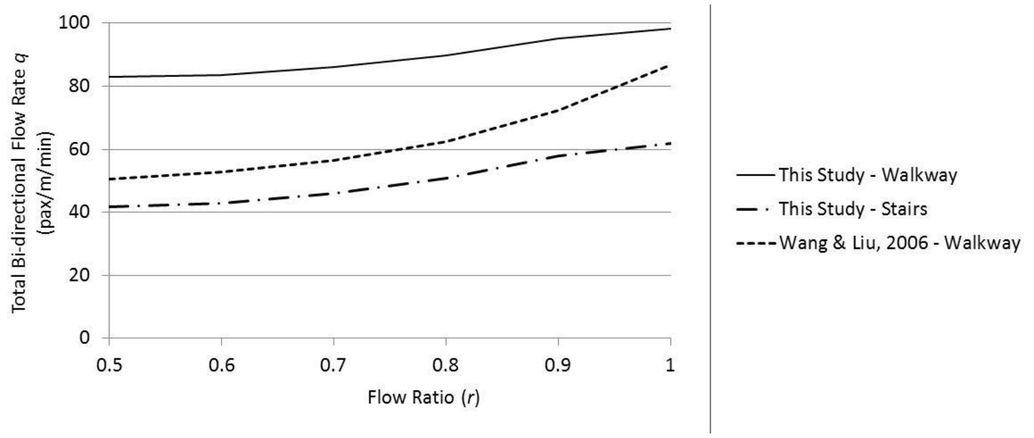


Figure 4.51: Comparison of total bi-directional flow rate on stairs & skywalks compared to data by Wang & Liu (2006)

From the results of the research conducted in this study, the total maximum skywalk bi-directional capacity reduces from 98.25 pax/m/min at *r* = 1.0 to 95.10 pax/m/min at *r* = 0.9, a drop of 3.21%. A higher drop of 6.09% (from 61.76 to 58.00 pax/m/min) is observed for stairs from *r* = 1.0 to 0.9. From *r* = 0.9 to 0.5, a drop of 12.83% and 27.81% is calculated for the skywalk and stairs respectively. From these results, it was found that the impact of flow ratio on capacity is more than double on stairs than on level skywalks.

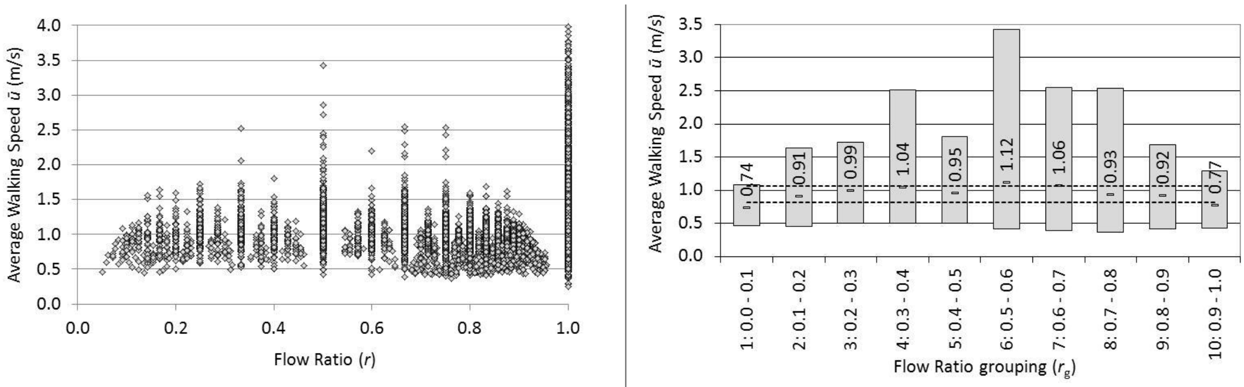
The simulation results by Wang and Liu (2006) revealed a greater drop in overall walkway bi-directional flow capacity from 86.76 p/m/min at *r* = 1.0 to 72.27 p/m/min at *r* = 0.9, a drop of 16.70% which corresponds to the 15% drop reported by Hoogendoorn *et al.* (2007) on level walkways. A drop of 30.05% is calculated for *r* = 0.9 to 0.5 for the Wang and Liu (2006) data which more closely corresponds to the 27.81% proportional drop calculated for the stairs observed in this research over the same flow ratio range.

Our results also reveal a much lower 15.62% and 32.21% overall drop in skywalk and stair capacity flow rates from *r* = 1.0 to 0.5 respectively, when compared to 41.74% reported by Wang and Liu (2006) for walkways. The results of the research presented in this study nevertheless confirms other research findings, which revealed that lower flow ratios result in lower capacities (Fruin 1987; Cheung and Lam 1997; Blue and Adler 1999; Lam *et al*. 2003; Wang and Liu 2006 and Hoogendoorn *et al*. 2007).

Despite the capacity drop correlation on stairs for flow ratios from *r* = 0.9 to 0.5 when compared to international literature, the results of this study however reveal a lower influence of flow ratio on maximum bi-directional capacity flow rates from *r* = 1.0 to 0.9 than proposed by other researchers. It can only be postulated that the reason for this is that a greater degree of bodily contact is considered acceptable in the South African context and hence the impact of the minor flow on capacity is far less than in developed countries where pedestrians try to maintain minimum acceptable interpersonal distances.

4.4.7 Impact of Flow Ratio on Walking Speeds

Figure 4.52 (*a.*) shows the scatter plot results of the average walking speed ($\bar{u}$) on skywalks plotted against the flow ratio (*r*) for all densities. The figure shows a large range of average speeds observed at *r* = 1.0 which is expected for uni-directional flows over all densities. To discount the large variation of purely uni-directional flow on walking speed, the walking speeds have been grouped according to flow ratio groupings (r_g) as shown in Figure 4.52 (*b.*) which includes all flow ratio data $0 < r < 1.0$ and therefore excludes the variation of values found within $r = 1.0$.



(a.) Scatter plot *(b.) Min, average and maximum u-values per r_g*

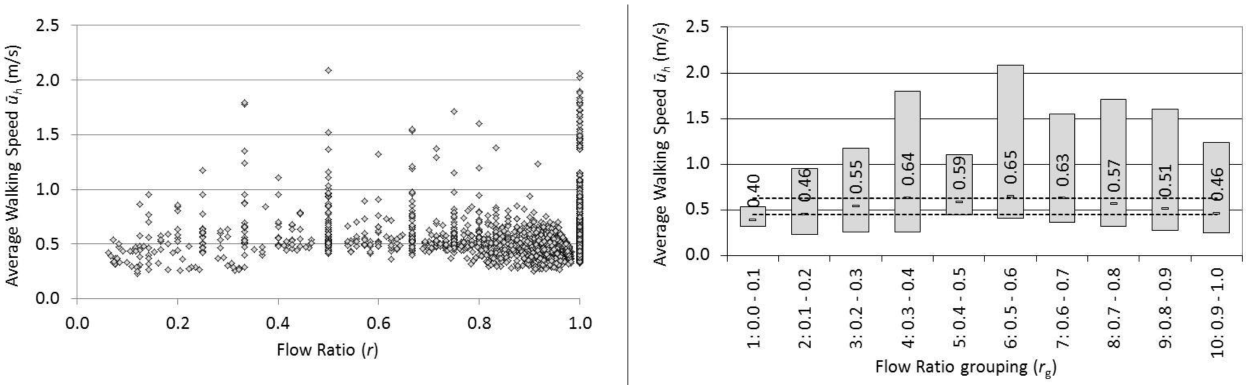
Figure 4.52: Average walking speed ($\bar{u}$) versus flow ratio grouping (r_g) relationship on skywalks (all densities)

Figure 4.52 (*b.*) shows the lower and upper limits for $\bar{u}$ at the 99% confidence interval (plotted as dotted horizontal lines) calculated according to:

$$m \pm t_{1-\frac{\alpha}{2}}, n-1.\frac{SD}{\sqrt{n}}$$

where m = mean value of $\bar{u}$, 1 - α = confidence interval, α = significance level, n = sample size and SD = standard deviation. The mean (m) value for the distribution of walking speeds ($\bar{u}$) is 0.94 m/s with a standard deviation (SD) of 0.12 m/s and calculated 99% lower and upper confidence limits of 0.817 m/s and 1.063 m/s respectively as shown in Figure 4.52 (*b.*). The average walking speeds of all flow ratio groupings, apart from r_g = 1, 6 and 10 fall within the 99% confidence interval.

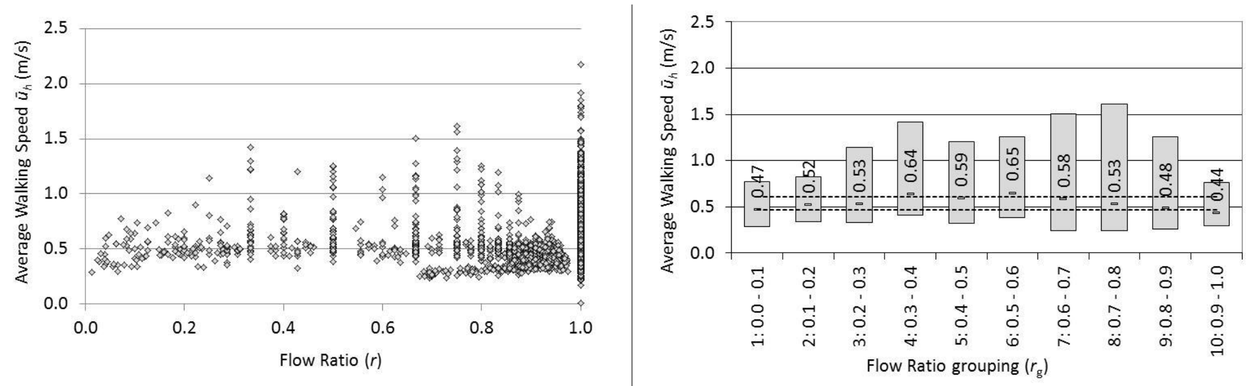
Figure 4.53 (*a.*) shows the scatter plot of the average horizontal walking speed ($\bar{u}_h$) versus flow ratio (r) for the ascending direction on stairs at all densities. The average walking speed (m) is calculated at 0.54 m/s with a standard deviation (SD) of 0.09 m/s and calculated 99% lower and upper confidence limits of 0.448 m/s and 0.632 m/s respectively as shown in Figure 4.53 (*b.*). The average horizontal walking speeds ($\bar{u}_h$) of all flow ratio groupings, apart from r_g = 1, 4 and 6 fall within the 99% confidence interval.



(a.) Scatter plot *(b.) Min, average and maximum u-values per r_g*

Figure 4.53: Ave. horz. ascending walking speed ($\bar{u}_h$) vs. flow ratio grouping (r_g) relationship on stairs (all densities)

Figure 4.54 (*a.*) shows the scatter plot of the average horizontal walking speed ($\bar{u}_h$) versus flow ratio (r) for the descending direction on stairs at all densities. The average horizontal walking speed (m) is calculated as 0.54 m/s with a standard deviation (SD) of 0.07 m/s and calculated 99% lower and upper confidence limits of 0.468 m/s and 0.612 m/s respectively as shown in Figure 4.54 (*b.*). The average horizontal walking speeds ($\bar{u}_h$) of all flow ratio groupings, apart from r_g = 4, 6 and 10 fall within the 99% confidence interval.

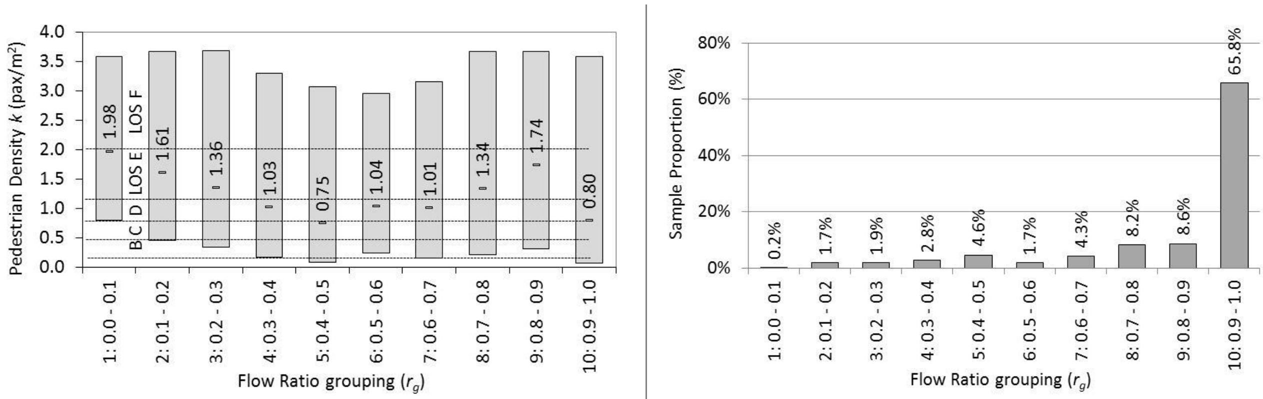


(a.) Scatter plot

(b.) Min, average and maximum u-values per r_g

Figure 4.54: Ave. horz. descending walking speed ($\bar{u}_h$) vs. flow ratio grouping (r_g) relationship on stairs (all densities)

Figures 4.52, 4.53 and 4.54 have, for both skywalks and stairs at all densities, given an indication that average walking speeds ($\bar{u}$) are unaffected by flow ratios (r). However, this cannot be a conclusive statement unless it can be shown that there is an even distribution of the data sample throughout densities for all flow ratio groupings (r_g). Since walking speeds are influenced by density, the density range for each of the flow ratio groupings together with the average density value was plotted to provide an indication of where the most observations were undertaken for a particular flow ratio grouping. Figures 4.55 (*a.*) and 4.56 (*a.*) show the range of density data observed per flow ratio grouping for the skywalks and stairs respectively. Figures 4.55 (*b.*) and 4.56 (*b.*) show the proportion of overall data observations made within a particular flow ratio grouping (r_g) for the skywalks and stairs respectively.

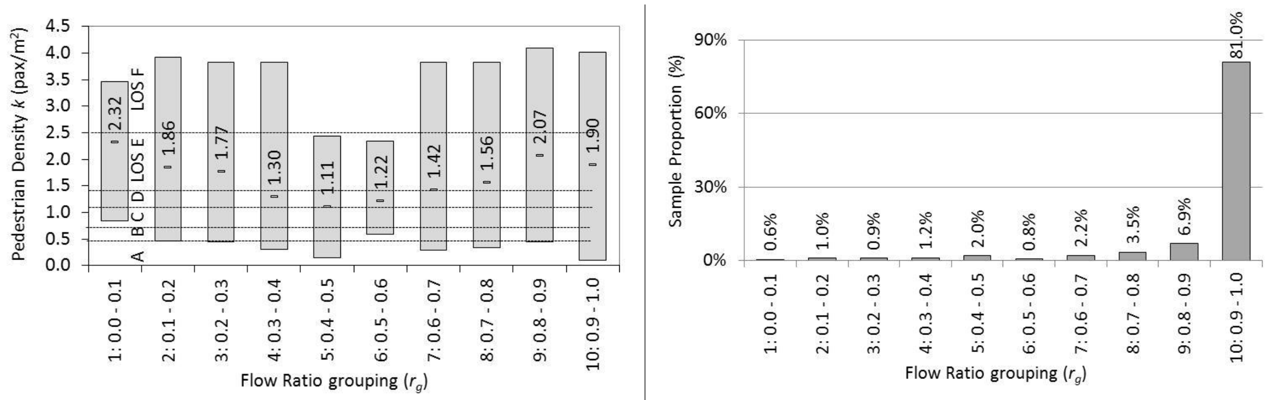


(a.) Distribution of density observations per flow ratio grouping

(b.) Sample proportion per flow ratio grouping (r_g); (n = 12,491)

Figure 4.55: Distribution of flow rate (q) data points per flow ratio grouping (r_g) for skywalks

Figure 4.55 (*a.*) shows that no observations were made in the LOS A bandwidth for flow ratio groupings (r_g) 1 through to 4. In fact, few observations were made in the LOS A bandwidth throughout for all flow ratio groupings. The average density values show that more observations were made at lower densities at flow ratio groupings (r_g) 4 to 7 than at flow ratio groupings (r_g) 1 to 3 and 8 to 10 where more observations were made at higher densities. Figure 4.55 (*b.*) shows that 65.8% of all skywalk observations were made at the flow ratio grouping r_g = 10, i.e. a flow ratio (r) between 0.9 to 1.0.



(a.) Distribution of density observations per flow ratio grouping (r_g)

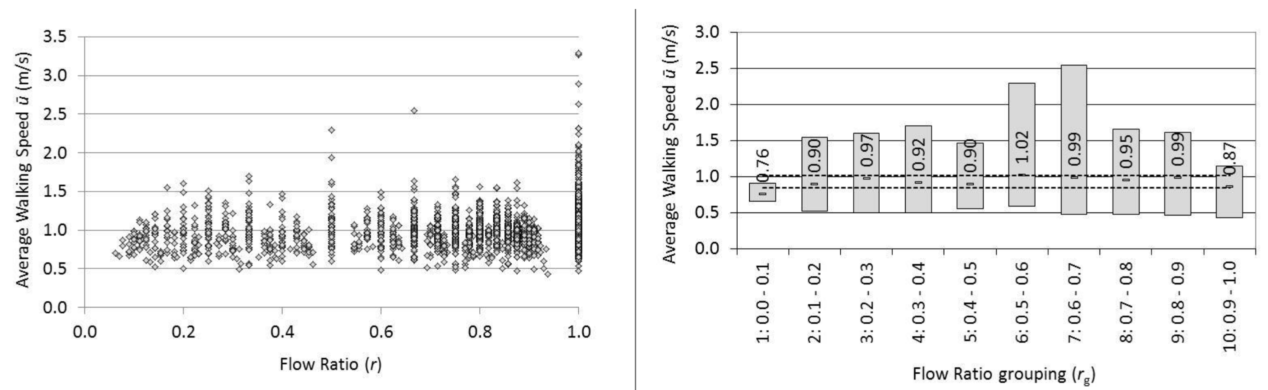
(b.) Sample proportion per flow ratio grouping(r_g);(n = 8,244)

Figure 4.56: Distribution of flow rate (*q*) data points per flow ratio grouping (r_g) for stairs

Figure 4.56 (*a.*) shows the observed range of densities per flow ratio groupings (r_g) for stairs. The figure shows the same pattern as that observed for skywalks where the average densities of observations made on stairs reduce from r_g = 1 to r_g = 5 and increase again to r_g = 10. No observations in the LOS F bandwidth were made for r_g categories 5 and 6. Figure 4.56 (*b.*) shows that a significant 81.0% of all stair observations were made at r_g = 10, i.e. a flow ratio between 0.9 to 1.0.

In order to determine the impact of density on the average walking speeds for each of the flow ratio groupings, the $\bar{u}$ versus r_g relationships for the LOS E density bandwidth was isolated and plotted. The LOS E density was selected as this is the only density bandwidth that is comprehensively covered in all flow ratio groupings and which has the most occurrences of the average density value within the particular bandwidth.

Figure 4.57 (*a.*) shows a plot of the $\bar{u}$ versus r relationship and Figure 4.57 (*b.*) shows the $\bar{u}$ versus r_g bar-graph for the LOS E density bandwidth only, plotted for the skywalk observations.



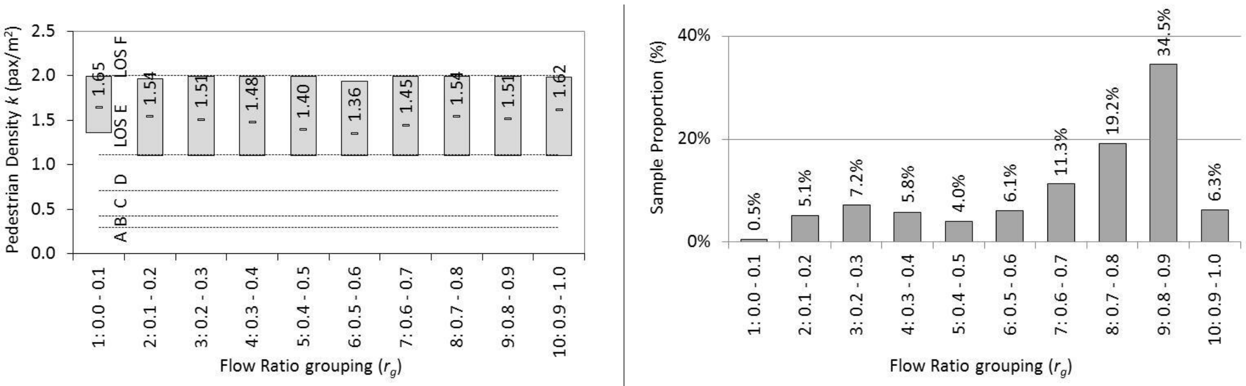
(a.) Scatter plot

(b.) Min, average and maximum u-values per r_g

Figure 4.57: Average walking speed ($\bar{u}$) versus flow ratio grouping (r_g) relationship on skywalks (LOS E only)

From the LOS E data, the average walking speed (*m*) is calculated as 0.93 m/s with a standard deviation (*SD*) of 0.08 m/s and calculated 99% lower and upper confidence limits of 0.848 m/s and 1.012 m/s respectively as shown in Figure 4.57 (*b.*). Whereas previously for the skywalk average speed observations, three flow ratio grouping speed readings fell outside the 99% confidence intervals; refer to Figure 4.52 (*b.*), the isolation of the data to the LOS E density bandwidth provided a more uniform set of average walking speed values for all flow ratio groupings, except for $r_g = 1$ (i.e. $r = 0.0$ to 0.1) falling below the lower limit. This is attributable to the high average density of recordings together with a very small proportion of the sample being conducted (viz. 0.2% of the sample) made for this flow ratio grouping.

Figure 4.58 (*a.*) shows that the flow ratio grouping range of observations at $r_g = 1$ does not extend across the full LOS E density range and has the highest average density value of all flow ratio groupings at 1.65 pax/m^2 with only 0.5% of the overall measurements undertaken in this (LOS E) density bandwidth as shown in Figure 4.58 (*b.*).



(a.) Distribution of density observations per flow ratio grouping (r_g)

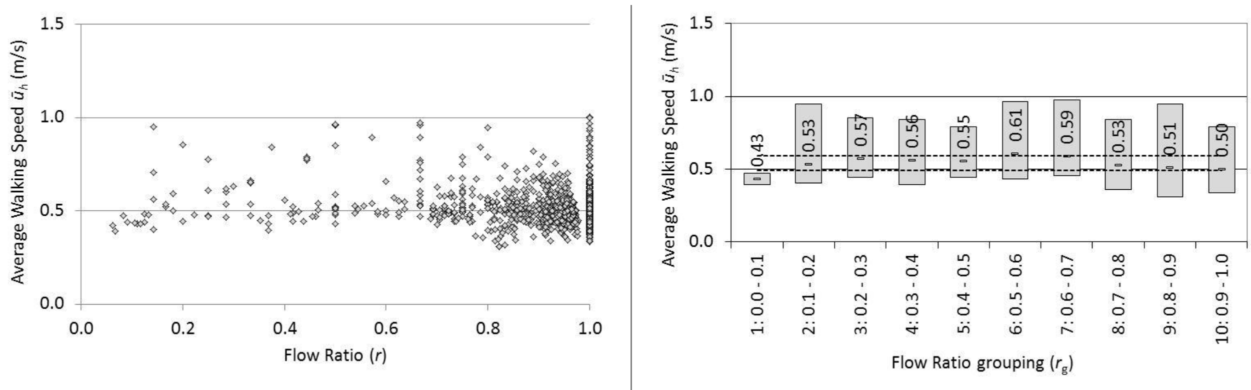
(b.) Sample proportion per flow ratio grouping(r_g); (n = 2,743)

Figure 4.58: Distribution of flow rate (*r*) data points per flow ratio grouping (r_g) for skywalks (LOS E only)

By isolating the density (*k*) criteria in determining the impact of flow ratio (*r*) on average walking speed ($\bar{u}$), the observations made above confirm that there is *no significant difference* between average walking speeds on level skywalks under various flow ratios (*r*) at capacity conditions (viz. LOS E). Due to the limited observations made at LOS A and B densities, a similar exercise could not be undertaken for free-flow conditions. The indication, based on the overall $\bar{u}$ versus *r* relationship for all densities, seems to suggest that average speed is not affected by flow ratio, but further investigations/studies should be conducted to confirm this observation for other LOS densities.

The observations made by Lam *et al.* (2003) and Wang and Liu (2006) also confirm that flow ratio (*r*) had no effect on average walking speeds for free-flow conditions on level walkways but both researchers observed slightly increasing values of average walking speed ($\bar{u}$) with increasing values of *r* (refer to Figure 2.11 and Figure 2.12 (*b.*) in Subsection 2.3.7) at capacity conditions, which was not observed in this research.

A similar exercise of isolating the average walking speeds for the LOS E density bandwidth was undertaken for the stair dataset. Figure 4.59 (*a.*) shows a scatter plot of the $\bar{u}_h$ versus *r* relationship and Figure 4.59 (*b.*) shows the $\bar{u}_h$ versus r_g bar-graphs for the LOS E density bandwidth only, plotted for the stair observations in the ascending direction only.

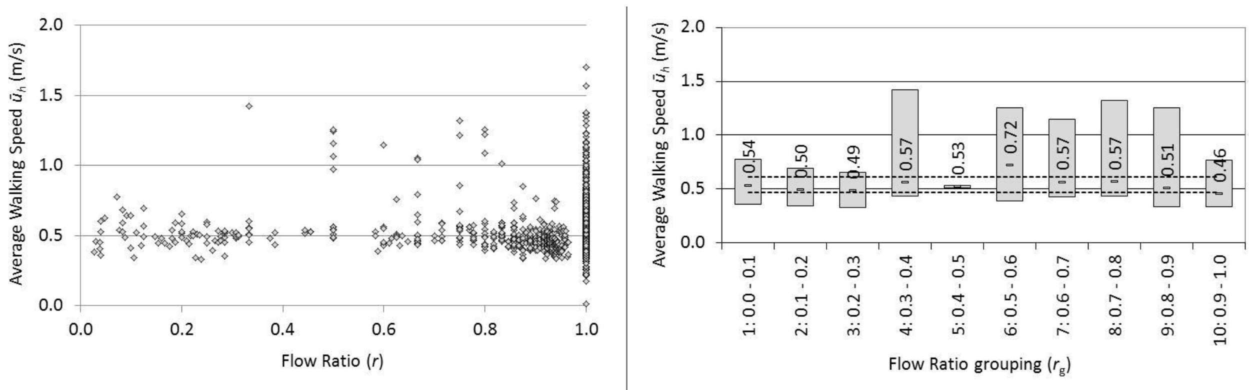


(a.) Scatter plot *(b.) Min, average and maximum u-values per r_g*

Figure 4.59: Average walking speed ($\bar{u}_h$) versus flow ratio (r) relationship on stairs (ascending, LOS E only)

The average horizontal ascending walking speed (m) is calculated as 0.54 m/s with a standard deviation (SD) of 0.05 m/s and calculated 99% lower and upper confidence limits of 0.489 m/s and 0.591 m/s respectively as shown in Figure 4.59 (*b.*). Again, due to the majority of observations being undertaken at a high average density in the LOS E density bandwidth viz. 1.4 pax/m^2 < k < 2.5 pax/m^2 shown in Figure 4.56 (*a.*) for flow ratio group (r_g = 1), the average ascending walking speed falls below the lower 99% confidence limit. All other walking speed values are within the confidence interval or marginally outside (viz. flow ratio group r_g = 6, i.e. r = 0.5 to 0.6).

Figure 4.60 (*a.*) shows a plot of the $\bar{u}_h$ versus r relationship and Figure 4.60 (*b.*) shows the $\bar{u}_h$ versus r_g bar-graphs for the LOS E density bandwidth only, plotted for the stair observations in the descending direction only.



(a.) Scatter plot *(b.) Min, average and maximum u-values per r_g*

Figure 4.60: Average walking speed ($\bar{u}_h$) versus flow ratio (r) relationship on stairs (descending, LOS E only)

The average horizontal descending walking speed (m) is calculated as 0.54 m/s with a standard deviation (SD) of 0.07 m/s and calculated 99% lower and upper confidence limits of 0.468 m/s and 0.612 m/s respectively as shown in Figure 4.60 (*b.*). The figure shows that the descending walking speed has a slightly larger confidence interval and that the average walking speeds for all flow ratio groupings within the LOS E bandwidth falls within the 99% confidence interval.

The horizontal walking speed versus flow ratio observations made for the stairs thus concur with the results of the skywalk data, and it is concluded that there is no significant difference between average ascending and descending horizontal walking speeds under various flow ratios (*r*) at capacity conditions (viz. LOS E). Again, due to the limited observations made at LOS A and B (refer to Figure 4.56 (*a.*)), a similar exercise could not be undertaken for free-flow conditions.

4.5 Boarding and Alighting Behaviour

Towards enabling quantitative assessment of boarding and alighting behaviour, observations were undertaken associated with clock time per passenger obtained directly off the video footage. With reference to Figure 4.61, the following boarding and alighting observation criteria are defined:

The moment the train stops is defined to occur at time $t = 0$;
The moment passenger alighting starts (A_S) occurs at time $t = t_1$;
The moment passenger alighting ends (A_E) occurs at time $t = t_2$;
The moment passenger boarding starts (B_S) occurs at time $t = t_3$;
The moment passenger boarding ends (B_E) occurs at time $t = t_4$;
The moment the train departs is defined to occur at time $t = t_5$;
By definition, since $t = 0$, the train dwell time is equal to t_5.

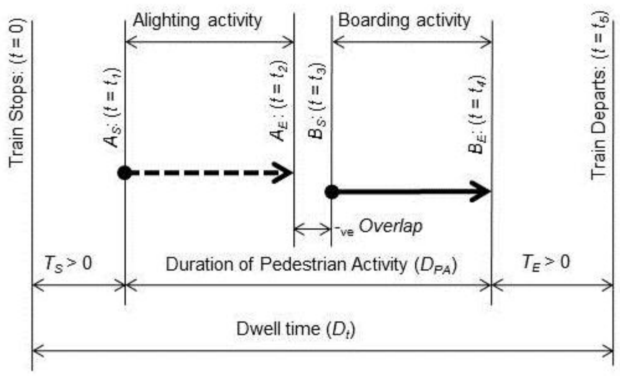


Figure 4.61: Definition of boarding and alighting parameters for the condition: $D_{PA} < D_t$

"*Time start*" (T_S) is defined as the difference between A_S and the train stop time and refers to the time it takes for alighting to start after the train has stopped. T_S is positive when alighting activity occurs after the train stops and is negative if alighting starts to occur before the train has stopped (as shown in Figure 4.62). Likewise, "*Time end*" (T_E) shows the difference between B_E and the train departure time. T_E is positive when boarding activity ends before the train departs and is negative if boarding continues until after train departure (as shown in Figure 4.62). The "*Duration of Pedestrian Activity*" (D_{PA}) is defined as the difference between B_E and A_S, or written as an equation as follows:

$$Duration\ of\ Pedestrian\ Activity = D_{PA}\ (sec) = B_E - A_S = t_4 - t_1$$

Note that there can be a (positive) overlap in the boarding and alighting activity (as shown in Figure 4.62 below) when $A_E > B_S$ or a (negative) overlap when $A_E < B_S$ as shown in Figure 4.61 above, both incorporated within the D_{PA}.

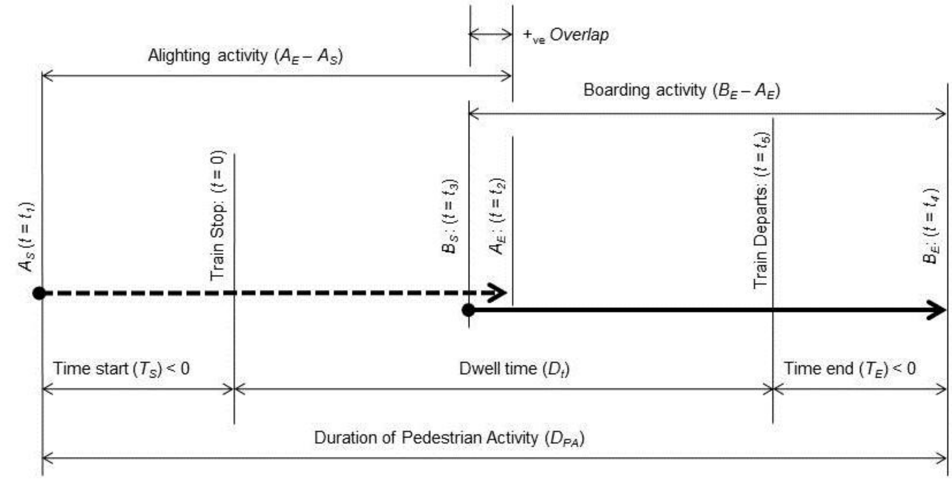


Figure 4.62: Definition of boarding and alighting parameters for the condition: $D_{PA} > D_t$

In order to determine the extent of dwell time used by B&A activity, we further define a "*Dwell utility*"[17] (D_u) function defined as the percentage of D_{PA} over the dwell time (D_t), written as an equation as follows:

$$Dwell\ utility = D_u\ (\%) = \frac{D_{PA}\ (sec)}{D_t\ (sec)}$$

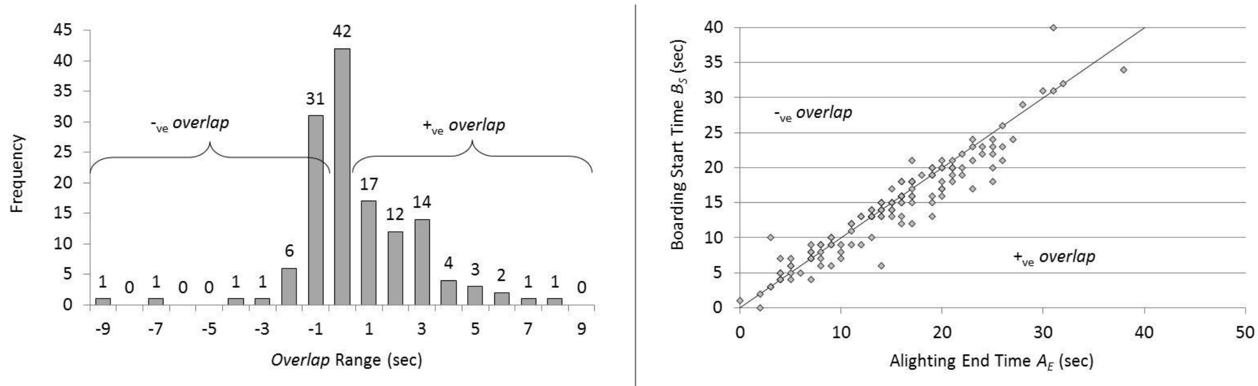
Note that the definitions apply to situations were both alighting and boarding occurs but specifically for Type 3 B&A behaviour i.e. where alighting occurs before boarding.

4.5.1 Boarding and Alighting Queue Discipline

From the observations undertaken in this research, it was found that B&A behaviour generally follows a Type 3 queuing trend as defined in Subsection 2.6.1. viz. that alighting is allowed to occur first before any boarding occurs. Unlike observations made by Zhang *et al.* (2008) who observed simultaneous boarding and alighting behaviour, there were very few occurrences where simultaneous boarding and alighting was observed in the local data, and when it did, generally occurred for brief periods towards the end of the alighting activity. In terms of the definitions made in this study, simultaneous boarding and alighting (overlap) occurs when $A_E > B_S$ and no overlap occurs when $A_E < B_S$. *Overlap* is then defined as the difference between A_E and B_S expressed as:

$$Overlap = A_E - B_S$$

When *overlap* is negative, it means that, after the alighting process is complete, there is a brief time interval equal to the absolute value of *overlap* where no activity occurs, before boarding starts. When *overlap* is positive, it means that there is a time interval equal to *overlap* when simultaneous alighting and boarding takes place. Figure 4.63 shows the results of the B&A overlap behavioural observations with (*a.*) showing the overall data sample overlap histogram and (*b.*) showing the scatter plot of the B_S versus A_E relationship.



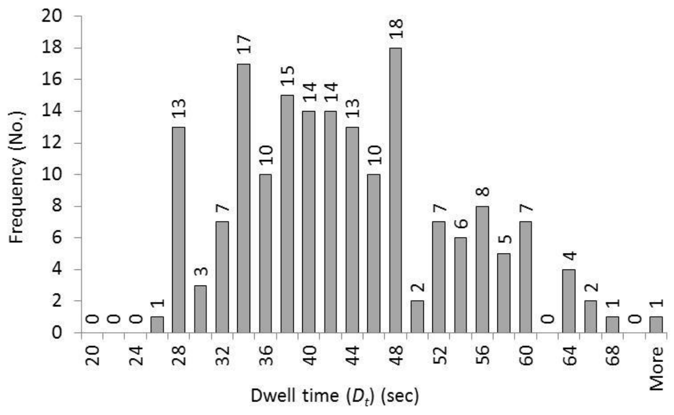
(a.) Overlap histogram *(b.) B_S versus A_E scatter plot*

Figure 4.63: Extent of boarding and alighting *overlap* in the observed data; (*n* = 137)

Figure 4.63 (*a.*) shows that 30.0% of the overall B&A observations had negative *overlap* with 39.4% of the observations showing simultaneous B&A activity (i.e. positive *overlap*) for various durations, mostly between one and three seconds only. Alighting behaviour followed immediately by boarding (i.e. at *Overlap* = 0) occurred for 30.6% of the observations. Apart from less than 5% of observations where simultaneous ($+_{ve}$ *overlap*) B&A activity occurred lasting for longer than four seconds, 92% of the observed data conformed to the predominant Type 3 B&A behaviour for the (-9 ≤ *Overlap* ≤ 4) condition.

4.5.2 Train Dwell Times

A total of 183 train dwell observation times (D_t) were recorded and analysed from the video recordings. Of these, five observations recorded were over two minutes in duration and were considered as outliers and consequently excluded from the dataset. The resulting final dataset sample (*n* = 178) had a mean dwell time of 42.92 seconds with a ±10.12 second standard deviation. The distribution of the dwell times (D_t) according to two second interval bins, is shown in Figure 4.64.



<u>Summary Statistics:</u>

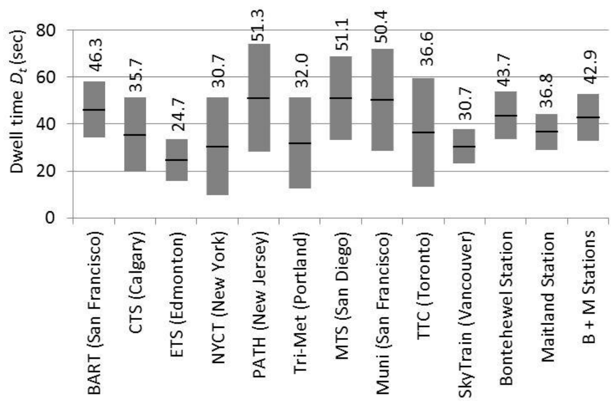
Sample size: n = 178
Dwell time (D_t) mean: 42.92 sec
Standard deviation: 10.12 sec
Minimum: 25 sec
Maximum: 82 sec

Note: Data sample excludes all outliers > 100 sec

Figure 4.64: Train dwell time (D_t) histogram

The standard deviation indicates a high variation in dwell times (D_t) despite the scheduled dwell time of 30 seconds for both Bonteheuwel and Maitland stations (CMC 1998). The mean dwell time calculated for Bonteheuwel and Maitland stations is 43.73 ± 10.15 seconds and 36.81 ± 7.65 seconds respectively.

The train dwell times observed at the Bonteheuwel and Maitland stations were also compared to the average dwell times observed at ten stations in the USA and Canada (TRB 1999b) and the results are shown in Figure 4.65. Note that bar lengths represent the extents of the standard deviation. The dwell time average of the combined data sample for Bonteheuwel and Maitland (B+M) stations is 42.92 seconds and is 10% higher than the American and Canadian average of 38.95 seconds.



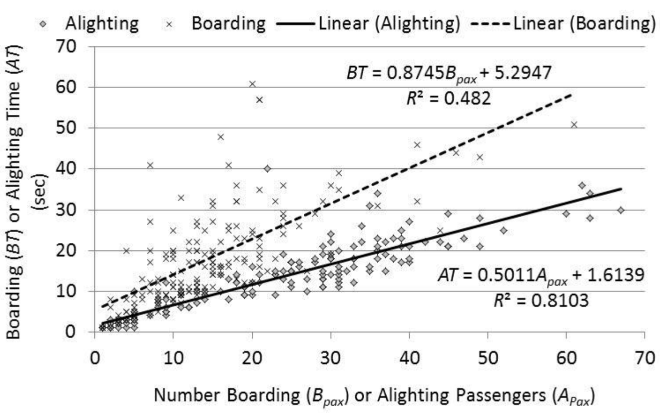
Sample size: n = 1,662

B+M denotes a collective Bonteheuwel and Maitland station sample set.

Figure 4.65: Bonteheuwel & Maitland Dwell times (D_t) vs. Canadian & American Dwell times; (Source: TRB 1999b)

4.5.3 Boarding and Alighting Rates

A plot of individual boarding passenger (B_{pax}) and alighting passenger (A_{pax}) volumes against boarding (BT) and alighting (AT) times respectively is shown in Figure 4.66. Linear regression applied to both datasets, together with the associated statistical attributes is also shown in the figure.



Summary Statistics:

Sample size: n = 162

Boarding behaviour:

$R^2 = 0.482$

P-value = 12.2×10^{-24}

t-statistic = 12.201

Alighting behaviour:

$R^2 = 0.8103$

P-value = 1.24×10^{-59}

t-statistic = 26.141

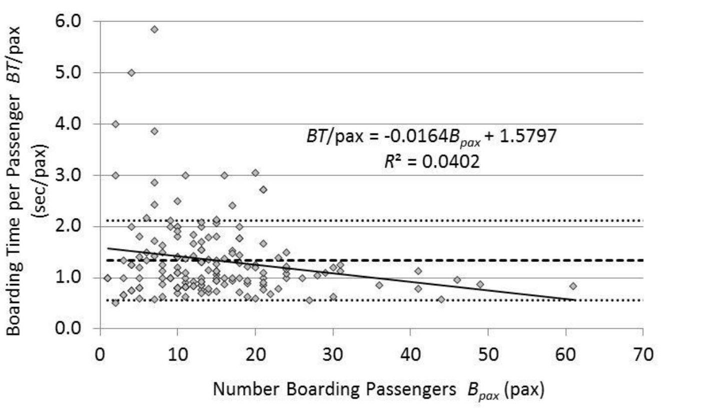
Figure 4.66: Relationship between boarding and alighting times per volume of boarding or alighting passengers

Figure 4.66 shows several things:

1. Both linear relationships are significant with *P*-values less than the 5% level of significance.
2. Boarding times (*BT*) are always slower than alighting times for all passenger volumes, but they also show more variation (both visually and by the relatively poor $R^2 = 0.482$ value). The reasons suggested for this are that boarding activity depends to a certain extent on the existing coach occupancy (which was not observed), the "funnel" effect where alighting takes place into greater space compared to boarding taking place into less space and/or that there is less urgency in the boarding process.
3. The variance of the alighting times (*AT*) is smaller than the boarding time (*BT*) variances with a good $R^2 = 0.81$ correlation coefficient suggesting that alighting is less influenced by coach occupancy and/or the greater urgency in the alighting process (in terms of passengers hurrying to get to their place of employment on time).
4. Boarding time (*BT*) appears to require approximately twice the amount of time for all passenger numbers than alighting time (*AT*) for the same passenger volume. For example 40 alighting passengers take approximately 20 seconds to alight whilst 40 boarding passengers take 40 seconds to board.

The results show significant differences in boarding and alighting times contrary to the findings of Daamen *et al.* (2008) who found, through controlled indoor laboratory experiments (refer to Subsection 2.6.3), that both boarding and alighting rates were similar. Whilst the boarding and alighting linear relationships indicated in Figure 4.66 above shows good correlation, it is important to appreciate the variance in the data as explained above.

The variance in the boarding data, represented as boarding time per passenger (*BT*/pax) is shown in Figure 4.67.



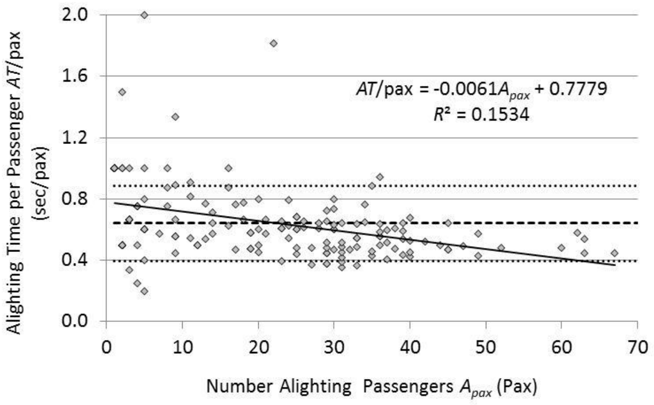
Summary Statistics:
Sample size: n = 162
Mean: 1.34 sec/pax
Standard deviation: 0.78 sec/pax
Minimum: 0.5 sec/pax
Maximum: 5.86 sec/pax

$R^2 = 0.0402$
P-value = 0.0105
t-statistic = -2.587

Figure 4.67: Relationship between boarding passenger volume (B_{pax}) and boarding time per passenger (*BT*/pax)

In the figure, the central (horizontal) dotted line represents the average boarding rate per passenger (1.34 sec/pax) with the straddling parallel dotted lines representing the standard deviation range from 0.56 to 2.12 sec/pax. A linear regression trendline fitted to the boarding data shows gradually reducing boarding times per passenger (*BT*/pax) for increasing boarding volumes (B_{pax}). This is likely due to a desire to secure a place on the train as people are less likely to loiter when the system is busy. Despite a poor $R^2 = 0.04$ correlation coefficient, the statistical significance of the relationship (with a *P*-value of less than 5%) indicates that the association cannot be ignored.

Figure 4.68 below shows a similar plot but for the alighting data.



Summary Statistics:
Sample size: n = 162
Mean: 0.64 sec/pax
Standard deviation: 0.24 sec/pax
Minimum: 0.20 sec/pax
Maximum: 2.00 sec/pax

R^2 = 0.1534
P-value = 2.54 x 10^{-7}
t-statistic = -5.385

Figure 4.68 Relationship between alighting passenger volume (A_{pax}) and alighting time per passenger (*AT*/pax)

The central (horizontal) dotted line represents the average alighting rate of 0.64 sec/pax. The standard deviation range in this case is 69.2% lower than the boarding data standard deviation range (viz. 0.48 sec/pax compared to 1.56 sec/pax). The straddling parallel dotted lines represent the standard deviation ranging from 0.40 to 0.89 sec/pax. As for the boarding data, the relationship cannot be ignored (statistically significant with a *P*-value of less than 5%), with the alighting rate trendline also showing gradually reducing alighting rate per passenger (*AT*/pax) for increasing alighting volumes (A_{pax}), but the linear correlation is poor at R^2 = 0.153.

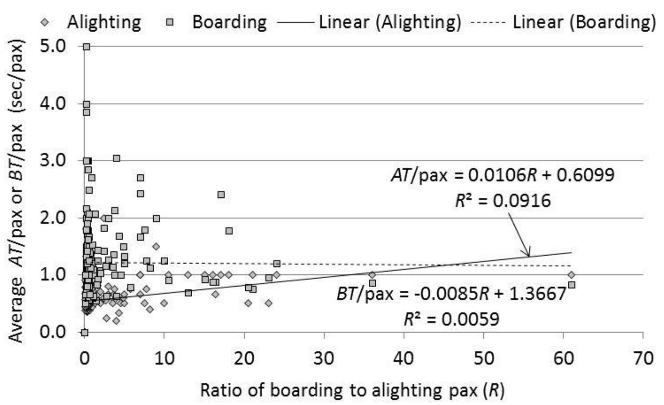
From the two graphs, it can be observed that alighting time per passenger (*AT*/pax) is less elastic to passenger volume than boarding times per passenger volume (*BT*/pax). In other words, greater alighting passenger volumes (A_{pax}) influence passenger alighting time (*AT*/pax) less than a corresponding increase in boarding passenger volume (B_{pax}) on passenger boarding times (*BT*/pax).

On the contrary, alighting rates are not significantly influenced by alighting volumes since the demand for space on platforms is not as competitive as for the boarding scenario where competition for coach space becomes a factor with increasing boarding volumes. Note that it is not practical to use the regression formula to predict alighting (*AT*/pax) or boarding rates (*BT*/pax) in sec/pax (for volumes exceeding 60 passengers per coach door) as both regression lines have a negative slope and *AT*/pax or *BT*/pax becomes negative after a certain number of passengers. The regression lines here merely indicate the apparent economies of scale with increasing passenger volumes. From the figures, boarding and alighting rates would tend to fall between the mean and the lower standard deviation values for volumes exceeding 40 passengers per door.

The large discrepancy in the observed boarding (*BT*/pax) and alighting (*AT*/pax) rates is therefore attributable to train crowding which can be argued would detrimentally influence the boarding data more so than the alighting data. It is noted that Cape Town trains (and in South Africa in general) are overcrowded during the peak hours (SARCC 2005) with the result that passengers frequently travel in-between coaches or hang from open doorways as shown in Figure 4.69. In South Africa, door closure failure does not prevent trains from operating.

Figure 4.69: Photographs showing typical commuter conditions during the PM peak hours of operation

A further objective of the boarding and alighting passenger observations was to identify whether different boarding and alighting volumes influenced the respective boarding and alighting rates at coach doors respectively. The argument being that a higher boarding volume bunching on the platform at coach door exits would likely slow down the disembarking (alighting) passengers. A plot showing the ratio of boarding to alighting passenger volumes (*R*) versus the alighting or boarding times per passenger is shown in Figure 4.70. Note that only *R* values greater than zero are included in the figure (i.e. it excluded a total of 16 data samples where boarding or alighting volumes are zero resulting in a reduced sample size, i.e. n = 162).



<u>Summary Statistics:</u>

Sample size: n = 162

<u>Boarding:</u>

R^2 = 0.00587

P-value = 0.3322

t-statistic = -0.973

<u>Alighting:</u>

R^2 = 0.0916

P-value = 9.07×10^{-5}

t-statistic = 4.016

Figure 4.70: Boarding and alighting times per passenger with varying ratios of *R*

As expected, the figure confirms that increasing boarding volumes (i.e. increasing *R* values) gradually impact on the alighting process and increases the alighting time per passenger (*AT*/pax) from 0.62 sec/pax at *R* = 1 to 1.25 sec/pax at *R* = 60. The increase in the *R*-ratio also decreases the boarding rate per passenger (*BT*/pax) from 1.36 sec/pax at *R* = 1 to 0.85 sec/pax at *R* = 60. Although the correlation trend agrees in principle to the simulation results made by Zhang *et al.* (2008); refer to Figure 2.25 in Subsection 2.6.3, the linear correlation for the boarding data determined in this research is not statistically significant (*P*-value > 5%) due to the clustering of the data points at *R* < 10.

Although the alighting data relationship is statistically significant (*P*-value < 5%), very poor correlation coefficients are calculated for both boarding and alighting datasets (R^2 < 0.1 in both instances). The main contributing reason for the poor correlation is the sensitivity of the ratio *R* for very low boarding volumes associated with higher alighting volumes that make a linear approximation of the data difficult.

4.5.4 Comparison with International Boarding and Alighting Rates

Controlled boarding and alighting experiments conducted by Daamen *et al.* (2008) revealed that door capacities reduced with increasing horizontal clearances (between platform and coach floor) as well as with increasing vertical clearances. They found a significant 25% drop in B&A capacity involving luggage-laden passengers, but the luggage size and proportion of passengers carrying luggage was unfortunately not specified in their study. In the research undertaken for this study, it was found that most pedestrians carried small knapsacks and/or shoulder handbags; refer to Figure 4.15 in Subsection 4.3.4. From on-site measurements, coach door widths for Metro 5M trains were found to be 1.30 m wide and 1.27 m wide for 8M trains. According to the specifications, door opening and closing times are 2.5 ± 0.5 seconds (Metrorail 2000).

Measured horizontal clearances between platform and coach floors were found to be in the range of 12 cm to 14 cm at both stations with vertical clearances between 28 cm to 30 cm. Figure 4.71 show photographs of a Metro 10M coach door opening showing the extents of platform clearances.

Figure 4.71: Photographs showing vertical and horizontal platform clearances

Table 4.18 tabulates the results of this study with other observations conducted worldwide. Note that Daamen *et al.* (2008) found that independent boarding and alighting rates were very similar and therefore reported the boarding and alighting rates as a collective B&A rate, rather than providing separate rates.

Table 4.18: Comparison of boarding and alighting rates with international results

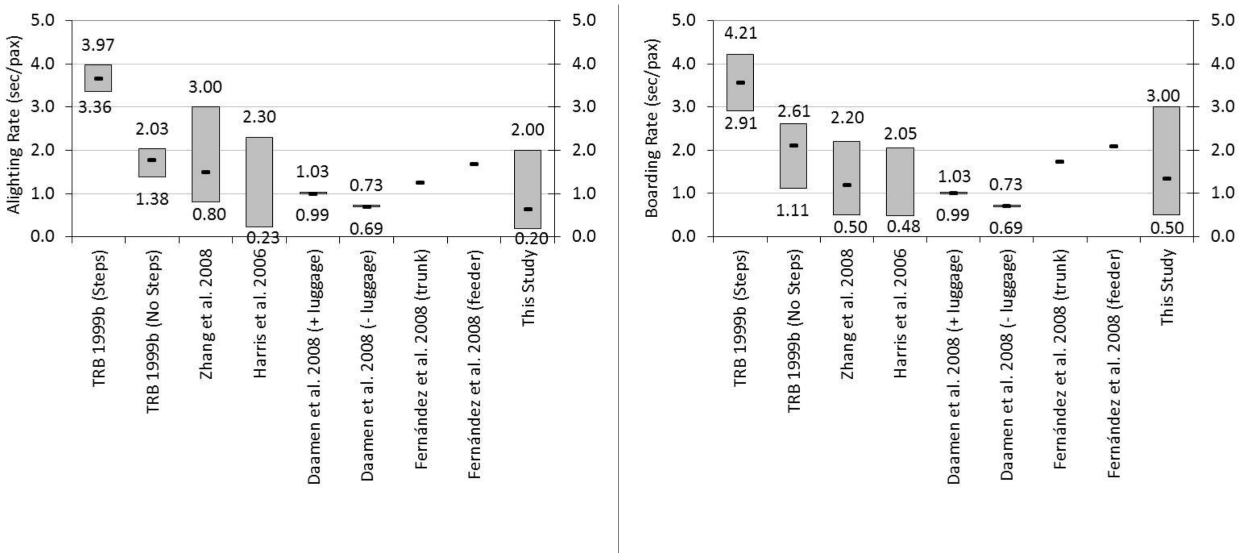
Source	**Description**	**Alighting rates (sec/pax)**	**Boarding rates (sec/pax)**
This Study	Bonteheuwel/Maitland (Cape Town)	Mean: 0.64 Range: 0.2 – 2.0	Mean: 1.34 Range: 0.5 – 3.0
TRB 1999b	Canada, USA (With steps)	Mean: 3.67 Range: 3.36 – 3.97	Mean: 3.56 Range: 2.91 – 4.21
	Canada, USA (No steps)	Mean: 1.77 Range: 1.38 – 2.03	Mean: 2.11 Range: 1.11 – 2.61
Harris and Anderson, 2006	30 International stations*[1]	Range: 0.23 – 2.30	Range: 0.48 - 2.05
Zhang *et al.* 2008	Three Beijing stations (Hong Kong)*[2]	Approx. Mean: 1.5 Range: 0.8 – 3.0	Approx. Mean: 1.2 Range: 0.5 – 2.2
Daamen *et al.* 2008	Laboratory experiments (No luggage)*[3]	0.67 – 0.80	
	Laboratory experiments (With luggage)*[3]	0.84 – 1.09	
Fernández *et al.* 2010	Santiago, (Chile) Trunk route buses	1.26	1.74
	Santiago, (Chile) Feeder route buses	1.68	2.08

*[1]: *Original results adjusted to a 1.3 m wide door opening.*

*[2]: *Data range and mean approximated from graph (Zhang et al. 2008)*

*[3]: *Original results adjusted to a 1.3 m wide door opening. Data for 15 cm horizontal gap shown only. Value ranges shown are average rates for the 20 cm and 60 cm vertical gap only.*

In this study, average alighting door capacity was found to be 0.64 ± 0.24 sec/pax, with a range of between 0.20 to 2.00 sec/pax. Figure 4.72 (*a.*) and (*b.*) shows respective alighting and boarding rates observed from international studies compared to the results of the observations made in this study. For the purposes of the plot; only reported data is shown; ie. if only ranges are reported in the literature, then the mean is not plotted and vice versa.



(a.) *Alighting Rates* (b.) *Boarding Rates*

Figure 4.72: Comparison of B&A rates with other international sources

From Figure 4.72 (*a.*), the average 0.64 sec/pax alighting rate observed in this study was found to be amongst the lowest recorded. The alighting rate data range observed in this study is similar to the range observed by Harris and Anderson (2006) with the average rate only slightly lower than the alighting rate of 0.7 sec/pax calculated for a 30 cm vertical clearance (using a linear relationship) from the Daamen *et al.* data.

The local boarding rate data appeared to be well within the ranges observed internationally. We note very high rates reported by the TRB (1999) data, particularly those associated with steps, but it is not clear if the data is associated with commuter travel or longer distance travel passengers, typically associated with leisure trip purposes. The average boarding door capacity was found in this study to be 1.34 ± 0.78 sec/pax, similar to the overall average door capacity ranges and averages observed by Harris and Anderson (2006) and Zhang *et al.* (2008) respectively. The data ranges shown by Daamen *et al.* (2008) in the graph are narrow as the values plotted refer to the average rate observed over a range of vertical gaps and the sensitivity in vertical clearance in this case (ie. from 20 to 60 cm) is not that sensitive.

A limitation of the boarding and alighting study conducted in this study was that no record of passengers carrying luggage was taken, nor was the crowding level on-board the train at the time of the boarding or alighting activity observed. On-board passenger volumes may explain the high range of the boarding rate observations. Due to the lack of boarding and alighting research worldwide, it should be noted that the results in this study are only compared against the results of first world countries and the comparison should be viewed within the context of this limitation.

4.6 Summary Discussion of Empirical Research Conducted

This section provides a summary discussion of the walking speed observations made as well as the fundamental relationships developed from the empirical data collected for this study. The fundamental relationships developed are also compared against those found in the literature. Table 4.19 provides an abridged summary of the most important findings of the empirical walking speed results reported in this chapter.

The mean walking speed ($\bar{u}$) of pedestrians (n = 2,783) observed on platforms for the entire range of densities was found to be 1.19 m/s with a standard deviation of 0.514 m/s. On Skywalks, the mean speed was slower at 1.11 m/s (n = 12,491) for the entire range of densities with a standard deviation of 0.384 m/s. The combined average ascending and descending horizontal walking speed on stairs was found to be 0.55 m/s (n = 9,988) for the entire range of densities with a standard deviation of 0.212 m/s. This combined average horizontal walking stair speed tends to lie towards the bottom of the range of free speeds of other international studies.

The mean walking speed ($\bar{u}$) of male pedestrians observed on all infrastructure types for the entire range of densities was found to be between 12.8% to 15.5% faster than for female pedestrians. Leaner/smaller built females were found to walk 19.5% slower than similar sized men and larger built females were found to be 17.7% slower than similar sized men. Despite the biased distribution of the female population towards the larger frame with the distribution of the male population biased towards the leaner frame, the percentage difference in walking speeds across genders is found to be similar for all person sizes.

Table 4.19: Summary of empirical data: walking speeds

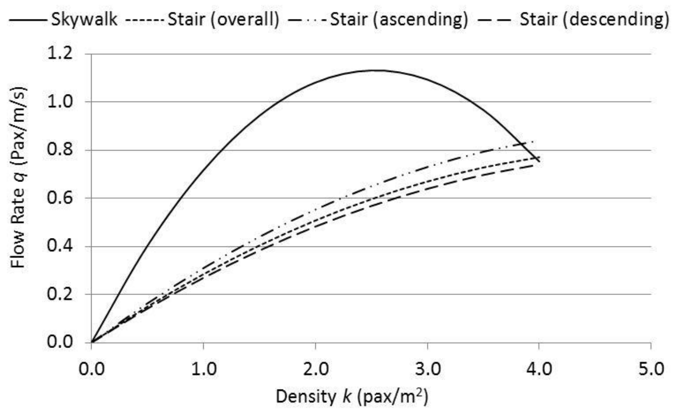
Variable	Comment	Mean	SD	Min	Max	*n*
Infrastructure:						
Platform	Inclu. waiting, boarding and alighting groups	1.19	0.514	0.44	5.82	2,783
Skywalk		1.11	0.384	0.25	5.37	12,491
Stairs	Both directions, riser 160 mm, tread 300 mm	0.55	0.212	0.01	2.18	9,988
Gender:						
Males	On Platforms	1.29	0.597	0.44	5.82	1,431
Females		1.09	0.382	0.44	4.21	1,352
Males	On Skywalks	1.19	0.426	0.25	5.37	7,166
Females		1.01	0.291	0.29	3.66	5,325
Males	On Stairs	0.57	0.234	0.01	2.17	6,892
Females		0.50	0.140	0.23	1.50	3,096
Person Size (Platform only):						
Lean/Small built	Both genders combined	1.33	0.67	0.48	4.21	141
Leaner than average		1.26	0.61	0.44	4.82	359
Average build		1.22	0.53	0.45	5.82	1,513
Slightly Larger than average		1.11	0.38	0.48	3.69	490
Large build		1.02	0.30	0.44	3.47	280
Group Size (Platform only):						
Singles	Males only	1.32	0.62	0.44	5.82	1,306
Groups (>2)		1.03	0.21	0.59	1.51	125
Singles	Females only	1.11	0.40	0.44	4.21	1,097
Groups (>2)		1.00	0.27	0.46	2.86	255
Baggage Size (Platform only):						
Nothing		1.34	0.69	0.50	5.82	383
Bag/article carried in one hand		1.22	0.57	0.46	4.69	513
Bag/article carried in both hands		1.07	0.26	0.68	1.45	18
Rucksack with both straps engaged		1.26	0.50	0.54	3.99	213
Rucksack with one strap engaged		1.15	0.45	0.44	5.31	1,500
Carrying other items		1.04	0.21	0.91	1.29	3
Platform Movement Type (Platform only):						
Alighting Passenger Group		1.24	0.54	0.46	5.82	1,888
Boarding Passenger Group		1.54	0.76	0.56	4.69	107
Waiting Passenger Group		1.04	0.32	0.44	4.07	788
Station Location:						
Platform: Bonteheuwel		1.23	0.54	0.44	5.82	1,831
Platform: Maitland		1.11	0.45	0.44	4.52	952
Platform: Overall		1.19	0.51	0.43	5.82	2,783
Skywalk: Bonteheuwel		1.23	0.44	0.25	55.37	4,675
Skywalk: Maitland		1.04	0.32	0.37	4.59	7,816
Skywalk: Overall		1.11	0.38	0.25	5.37	12,491
Stairs: Overall (Bonteheuwel Station)		0.55	0.21	0.01	2.18	9,988

For the overall sample, the average walking speeds of singletons on platforms was found to be 16.4% faster than those walking in groups of two. The average speed of females walking alone on platforms was observed to be 18.9% slower than men walking alone. It is interesting to note that the observed average walking speed for female groups of two or more was only 3% slower than that observed for male groups.

For the observations made on platforms, it was observed that carrying luggage significantly affected the average walking speed. Unencumbered pedestrians (n = 383) walked fastest at 1.34 m/s followed by those pedestrians wearing a rucksack with both straps over the shoulders (n = 213) at 1.26 m/s. Pedestrians who were observed to carry baggage/parcels in both hands (n = 18) were found to walk the slowest at 1.07 m/s. Pedestrians who walked carrying luggage in one hand (n = 513) were observed to walk at an average speed of 1.22 m/s. From the platform empirical dataset, an average waiting walking speed of 1.04 m/s (n = 788) and an average alighting walking speed of 1.24 m/s (n = 1,888) is calculated, a difference of 19.2%. It is concluded that the high boarding speed of 1.54 m/s (n = 107) observed in this study is as a result of individual pedestrian anxiety due to the possibility of not getting on board due to the high boarding demand or coach occupancy levels.

The results of the platform observations revealed that there are statistically significant differences in average walking speeds at different locations, for the same time period, even when isolating the variables for both gender types. The observations made in this study indicate that geographic location influences walking speeds for both gender types.

Figure 4.73 provides a plot of the fitted flow rate (q) versus density (k) relationships for the skywalk and stairs observed in this study. From the figure, it can be observed that the skywalk function follows a distinct parabolic function with a maximum flow rate capacity (q_c) of 1.13 pax/m/s at a critical density (k_c) of 2.53 pax/m^2. This maximum flow rate value (q_c) coincides with the start of the LOS E density bandwidth for level surfaces (viz. 1.10 pax/m/s < LOS E < 1.37 pax/m/s) but the critical density (k_c) is well within the LOS F bandwidth (LOS F > 2.0 pax/m^2) as defined by the TRB (1999c).



Fitted equations:

Skywalk:

$q = -0.1762.k^2 + 0.8932.k$

$r^2 = 0.5368$

Stairs (overall):

$q = -0.0366.k^2 + 0.3152.k$

$r^2 = 0.576$

Stairs (ascending direction):

$q = -0.0333.k^2 + 0.3434.k$

$r^2 = 0.7215$

Stairs (descending direction):

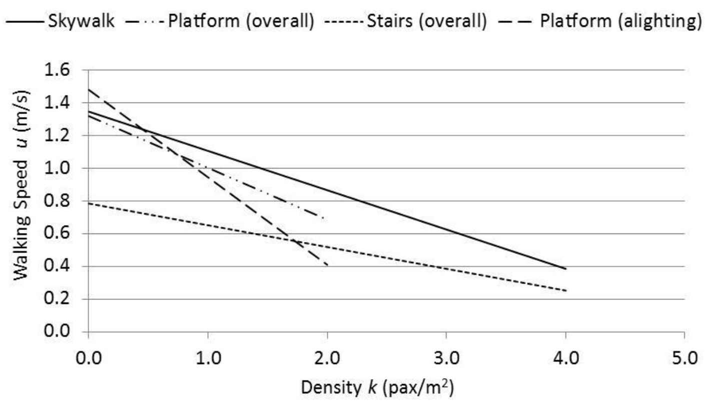
$q = -0.0281.k^2 + 0.2976.k$

$r^2 = 0.5192$

Figure 4.73: Skywalk and stair flow rate (*q*) vs. density (*k*) relationship results

The fitted flow rate (q) versus density (k) stair function, despite observation points well within the LOS F density criteria (i.e. k > 2.50 pax/m^2), does not reach a capacity value. A maximum observed flow rate value of 0.7 pax/m/s is calculated using the fitted equation at a density k value of 4.0 pax/m^2.

Figure 4.74 shows the fitted walking speed (u) versus density (k) equations for the skywalk, platform and stair observations. Note that the ascending and descending equations were not plotted for the stair relationship as the both lines coincided with the overall stair data plot. Both level surfaces (viz. the skywalk and the platform) begin with free-flow speeds of approximately 1.3 m/s. The figure shows that the platform speeds are more affected by increasing density values than the skywalk data. This is due to the impact of stationary (waiting) pedestrians and/or cross-flow pedestrians in the platform measurement area of the platforms, which does not occur as frequently in the skywalk measurement area.



Fitted equations:

Skywalk:

$u = -0.24.k + 1.3466$

$r^2 = 0.176$

Stairs (Overall):

$u = -0.1329.k + 0.7853$

$r^2 = 0.3112$

Platform (overall):

$u = -0.3163.k + 1.3193$

$r^2 = 0.0335$

Platform (alighting):

$u = -0.5343.k + 1.4793$

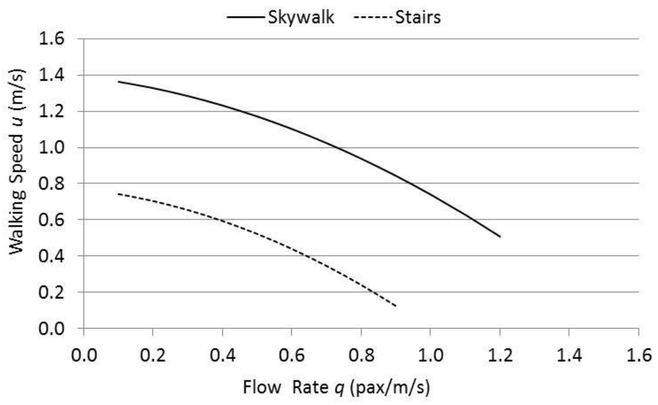
$r^2 = 0.0706$

Figure 4.74: Skywalk, platform and stair walking speed (*u*) vs. density (*k*) relationship results

The staircase fitted equation begins at a free-flow horizontal speed (u_h) of approximately 0.8 m/s and is the least affected by density for all infrastructure types as indicated by the relatively flat (inelastic) slope of the fitted linear equation.

The platform u vs. k equation fitted for alighting passengers is the most sensitive to variation in density. Unlike both the stair and skywalk data, no data points were observed beyond a density of 2.0 pax/m^2 (i.e. LOS F conditions) on the platforms, despite undertaking numerous surveys during peak periods. Due to the ample 9.0 m width of the platforms, alighting pedestrians are able to spread themselves out quickly over the entire width of the platform, which explains why no densities exceeding 2.0 pax/m^2 were observed. The sensitivity of density on platform speed observed for alighting passengers is likely due to the nature of the data collection sample, i.e. the first pedestrians who alight from trains (and who subsequently enjoy a good LOS at low density) are the ones who either choose to run or walk faster to keep ahead of the ensuing alighting crowd.

Figure 4.75 provides a plot of the fitted walking speed (u) versus flow rate (q) relationships for the skywalk and stairs observed in this study. From the figure, it can be observed that the curvilinear functions are parallel to each other but do not provide a maximum flow rate value. Despite the skywalk q vs. k relationship providing a critical capacity flow rate q_c value of 1.13 pax/m/s at a critical density k_c of 2.53 pax/m^2 (refer to Figure 4.73), the *u* vs. *q* relationship data does not reveal a critical walking speed u_c value at the same critical capacity flow rate.



Fitted equations:

Skywalk:
$u = -0.4255.q^2 - 0.2238.q + 1.3892$

Stairs (Overall):
$u = -0.5545.q^2 - 0.2177.q + 0.77$

Figure 4.75: Skywalk and stair walking speed (*u*) vs. flow rate (*q*) relationship results

Figure 4.76 provides a comparison of the *q* vs. *k* relationship identified for the skywalk in this research against that of other published relationships. Apart from the data observed by Fruin (1971), all the other datasets, including the skywalk dataset observed in this research, produced a maximum or capacity flow rate value q_c.

The observations of this research did not exceed density levels of 4.0 pax/m^2, well into the density LOS F bandwidth. From the figure, the capacity flow rate (q_c = 1.13 pax/m/s) observed in our data closely approximates the capacity flow rate observed by Weidmann (1993) but at a slightly higher critical density k_c = 2.53 pax/m^2. Apart from the data by Fruin (1971) and Weidmann (1993), all other research datasets observed capacity flow rates well in excess of 1.2 pax/m/s.

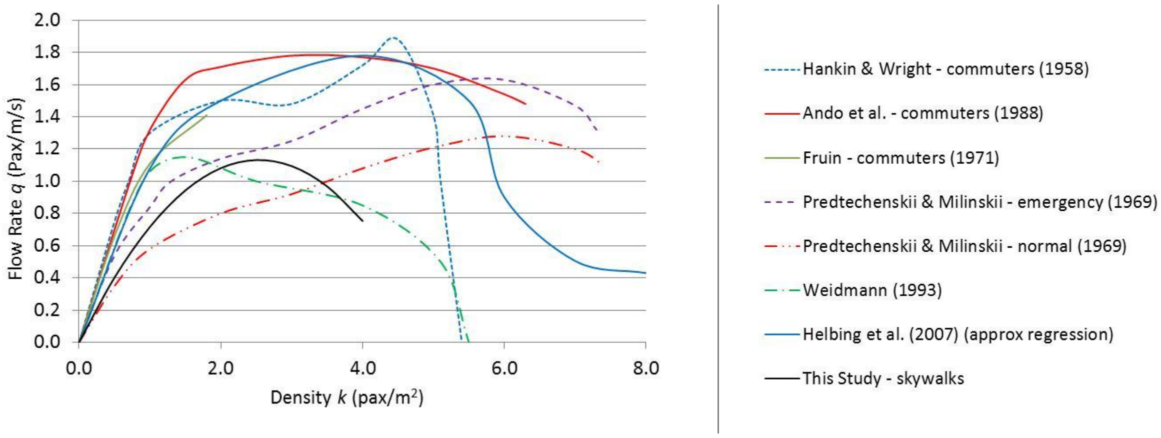


Figure 4.76: Comparison of skywalk *q* vs. *k* relationship with other international research relationships

Figure 4.77 provides a comparison of the *u* vs. *q* relationship identified for the skywalk and platform infrastructure types observed in this research against that of other published relationships. Apart from the datasets by Hankin and Wright (1958); Predtechenskii and Milinskii (1969) and Ando *et al.* (1988), the free-flow speeds observed for skywalks and platforms in this study at densities of less than 1.0 pax/m^2 generally coincide with the fitted curves of other researchers. Certainly, for the *u* vs. *k* relationship, there is less of a variation in data than observed for the *q* vs. *k* relationship.

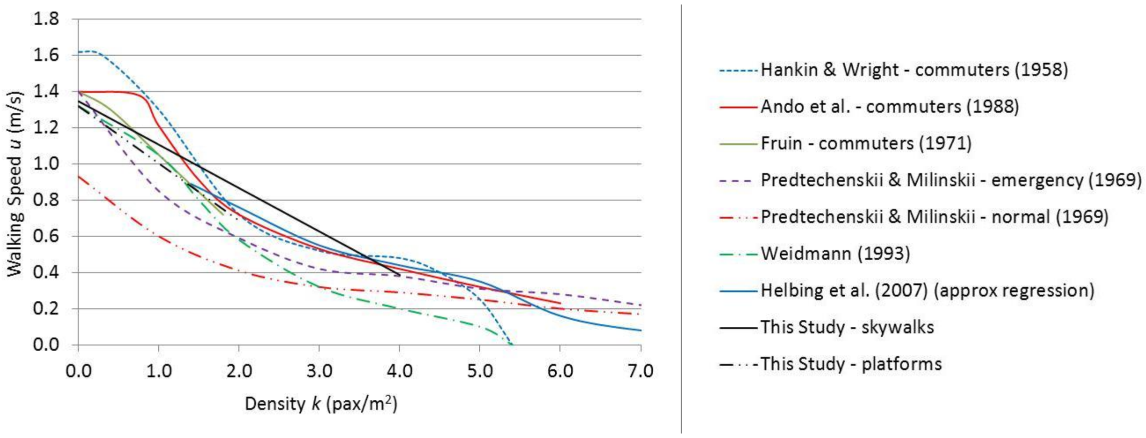


Figure 4.77: Comparison of skywalk & platform *u* vs. *k* relationship with other research relationships

The curves of each of the fundamental relationship diagrams shown above are the result of statistical estimation from the scatter plots and are used to indicate the change trend of the empirical scattered dots. According to the fundamental relationship between pedestrian flow (*q*), density (*k*), and speed (*u*), some characteristic values of pedestrian flow, such as the observed capacity, critical density (density at capacity) and free-flow speed could be obtained and is summarised and tabulated in Table 4.20.

Table 4.20: Typical characteristic values of pedestrian flow parameters observed

Facility	Sample no. (*n*)	Flow rate capacity q_c (pax/m/s) (from equation)	Flow rate capacity q_c (pax/m/s) (from 99th %tile)	Critical density k_c (pax/m^2)	Free-flow (LOS A) speed u_f (m/s)
Skywalk	12,491	1.13	1.543	2.53	1.33 ± 0.54
Stairs (overall sample)	8,244	0.70	-	4.00	-
Descending stairway	5,589	no maximum	0.959	-	0.80 ± 0.33
Ascending stairway	2,655	no maximum	0.873	-	0.77 ± 0.39
Platform (Alighting pax)	1,888	-	-	< 2.00	1.36 ± 0.67

From the shapes of the fundamental curves developed in this research and despite observations conducted under high capacity conditions for the stairs and skywalks (viz. well within the LOS F density standards), it was found that the flow rate data points did not drop significantly once the capacity flow rate (q_c) for the *q* vs. *k* curve was achieved; and in fact no capacity flow rate drop was observed for the *u* vs. *q* curves.

This is the same observation made by Johnson (1977) and more recently by Ye *et al.* (2008), although their range of observations were restricted to densities of up to 2.5 pax/m^2 (LOS F boundary for staircases). Their statement that fundamental curves do not exist past capacity points thus seems to apply to the data observed in this study.

Note that the stair fundamental diagram, due to the greater degrees of freedom which influence the fundamental diagram, has not been plotted. These degrees of freedom range from travel direction or flow ratio (*r*), the influence of riser and tread dimensions and the impact of stair length on exhaustion levels, thus offering a very wide range of possibilities. As indicated by Schadschneider *et al.* (2009), "*it is essentially due to the dependence on incline that there are no generally accepted fundamental diagrams for movement on stairs*".

The results of the empirical study presented in this section should prove useful both to designers and to modellers of railway station spaces for pedestrians in several important regards. First, our description of several of the most fundamental elements of movement behaviour may be used by modellers to assign realistic values to each modelled pedestrian according to a range of simple parameters (for example, desired walking speed) with particular application to the South African context. The empirical investigation of which factors affect the values of these parameters also provides an insight into how a realistic distribution of values might be chosen for a particular environment or situation: for example, modelling a railway station with a higher female usage should take into account the slower walking pace of such pedestrians potentially taking up more space on the pavement (for example, as a result of walking in groups, or transporting large shopping bags), and the effects this might have on the allocation of infrastructure space. Second, our results should prove useful not only in the calibration of model movement parameters by planners and modellers of pedestrian spaces, but also in highlighting a number of behavioural phenomena that might be expected to emerge from any realistic model of individual movement behaviour. With respect to the observations made, behavioural phenomena such as the occupation of staircases by waiting passengers restricting staircase widths (and capacities) needs to be taken into account.

Whilst the empirical research was primarily conducted to calibrate the development of the SP-model, it has also helped contribute to a more comprehensive understanding of how pedestrians negotiate railway station spaces essential to the development and calibration of other microscopic models that aim to help in the design of effective pedestrian spaces.

The fundamental macroscopic functions determined in this section are expected to find application in the planning and design of railway stations in particular. It represents an evolutionary contribution to an active field of research and is a resource for those who are developing pedestrian models in practice. It is these macroscopic functions that the SP-model is largely based upon.

Similar empirical studies are encouraged to be carried out at different walking facilities so as to enhance pedestrian modelling theory for the design and operation of not only railway stations but other walking facilities. Findings derived from this research are expected to be directly applicable in South Africa or in other African cities with similar pedestrian characteristics.

In conclusion, the most important finding from the empirical study and analysis is that it is necessary to select the appropriate criteria when calculating LOS and to take into account the "*LOS-mismatch*" phenomena resulting from variations in the fundamental relationships.

5. DEVELOPMENT OF THE SPATIAL PARAMETERS (SP)-MODEL

The development of a spreadsheet model to calculate the dynamic longitudinal pedestrian levels-of-service (LOS) of various infrastructure elements for South African concourse railway stations is presented in this chapter. The model permits the designer to focus on a particular problem area/s which limits the capacity of the entire station. Primarily intended for the design assessment of new facilities, the model can also be used to assess the acceptable operational lifespan of existing stations and identify the timing of and extent of upgrade requirements.

The chapter begins with a background of past macroscopic models developed and used by the author and the need for a revised SP-model is motivated. This is followed by describing the SP-model development process including a discussion on the mesoscopic algorithms used in the model and some of the limitations and shortcomings of the model. The calibration of the default model parameters is then discussed followed by a concluding chapter recommending further improvements to the model.

5.1 Introduction

As product lifecycle times decline and competition for resources increases, there is an increasing need to reduce both the duration and cost of designing new products and the processes to manufacture these products. With increasing rail patronage on some routes, existing stations have become more congested and the adequate design of new stations becomes increasingly important.

The Spatial Parameters (SP)-model will be useful in sizing new concourse facilities, to determine if adequate space will be available at critical points and to balance the overall allocation of space. For existing stations, the model will provide a means to determine what kind of remedial measures can be taken where unacceptable congestion or LOS occurs.

This chapter is confined to an overview of the model functions and requirements. Each function and/or type of requirement will be discussed in detail in the following subsections. Note that this chapter is not considered as an instruction manual on how to use the model, which is attached separately as Appendix L. The instruction manual provides more details with regard to the input requirements.

5.1.1 Background to the Formulation of the SP-Model

The SP-model originally started its development as a SP-matrix in 2007 when the author was involved in the transportation assessment of the Athlone, Heideveld and Langa (AHL) railway station upgrade projects in Cape Town, South Africa (J&G 2007a; J&G 2008). As there are dependant relationships between certain spatial parameters, the spreadsheet proved to be a useful tool and incorporated traffic engineering, pedestrian flow theory, queuing theory and static level-of-service (LOS) assessment criteria.

The SP-matrix was a simple Microsoft Excel spreadsheet with all inputs and outputs conveniently presented on an A4 landscape paper format. A sample of the SP-matrix (version 02) is attached in Appendix Q. After several trial versions, developed during the project process, the SP-matrix became the benchmark spreadsheet for the design of the AHL stations although it was acknowledged at the time that the model was an evolving model and its outputs were not to be considered as rigid spatial requirements.

The fundamental flaw of the SP-matrix was that there was no longitudinal assessment and the calculated worst-case LOS was a single static output based purely on the macroscopic peak one-minute flow rate. Train scheduling and frequency, incorporating "*micro-peaking*", which greatly affects station infrastructure requirements was also not considered. The entire station infrastructure was in fact determined according to the single peak one-minute pedestrian volume inputted by the user. These shortcomings led to the need to completely reconsider the spreadsheet model as addressed in this dissertation.

5.1.2 Consideration of Model Platforms

The macroscopic SP-matrix spreadsheet proved very useful in the simulation of physical movement of pedestrians in large uniform streams, but as stated before in Subsection 2.1.4, it can be erroneous if the streams are highly variable both in volume and direction, which is typically the case in railway station environments. Microscopic models on the other hand require extremely detailed inputs and require experienced and specialist modellers to use the programs.

The development of microscopic models incorporating pedestrian origin-destination (OD) inputs and 3D network building requirements is particularly time intensive. The need is to find a model platform that avoids the macroscopic pitfalls associated with aggregated passenger volumes but also avoids the resource and time demands required by microscopic modelling. A decision was thus made to use a simple new approach which can be considered to be a mixture of the macroscopic and the microscopic approach. Microsoft Excel was the platform selected for the model, a software environment that is familiar to most people and is easy to program and use.

The SP-model is therefore essentially a mesoscopic model with the central idea being to describe pedestrian dynamics as flow on a network with links of limited capacities. Mesoscopic models are typically represented by small groups of pedestrians with similar characteristics.

This allows for the evaluation of pedestrian dynamics without the need to simulate individual pedestrian requirements. Parameters entered into the SP-model can be adapted to the situation that is studied and in this instance, has been based on empirical results specifically conducted in this research and thus adapted (or calibrated) to local South African conditions.

A mesoscopic space-time-volume method of calculation is used in the SP-model allowing "*dynamic*" longitudinal outputs to be produced which takes the relationship between flow and density into consideration. The disadvantage of the space-time-volume method is that it requires considerably more input than the macroscopic SP-matrix, but the SP-model user interface (UI) makes the input process simple with the overriding benefit of longitudinal outputs approximating those of microscopic modelling results. Comparison between the SP-model results and microscopic model results are discussed further in Chapter 6.

5.2 Model Development

The model proposed in this study builds upon the mesoscopic modelling concepts proposed by Tolujew and Alcalá (2004) by incorporating restrictive capacities of walkways, platforms and staircases and providing a longitudinal level-of-service output. The ability to quickly change the model infrastructure attributes and input parameters is possible making the mesoscopic approach very practical and easy to use, typically uncommon in commercial simulation programs.

The mesoscopic category of modelling does not focus on individual pedestrians, but considers the idea of grouping individuals for analysis purposes. This means that each pedestrian is not modelled individually (as is done in microscopic modelling) but is classified into groups of pedestrians for which each has its own rules of behaviour (eg. walking speed histogram).

This simplification is considered appropriate because the SP-model does not need to identify the state of a single person but rather the number of persons in a particular measurement area at time *t*. The main components of the SP-model are groups of pedestrians (in this instance grouped according to railway coaches) and a predefined station network representing the station environment. The network assumes a standard platform(s)-staircase(s)-concourse-foyer-skywalk infrastructure link, each associated with a walking distance and width (area) dimension. Each pedestrian group is then assigned to move through the network according to a particular walking speed histogram. The difference between pedestrians exiting and entering the particular infrastructure link or area represents the number of pedestrians occupying the infrastructure link or area. Since each link has dimensions, the fundamental macroscopic parameters viz. flow, speed and density can then be calculated.

The SP-model uses a discrete time step size of one second. Position changes of persons within the mesoscopic groups are mapped in the model in terms of a space-time-volume matrix in such a way that matrix cell values are updated at the end of each one-second time interval.

5.2.1 SP-Model Requirements

The model is built in Microsoft-Excel and is easy to use. There is no complicated sequence of macros to run and the output spreadsheets can be plotted out on A4 portrait paper.

The underlying requirement of the model is that it should be simple to use. To create a complicated model defeats the objective of this study as there are many commercial models (particularly microscopic ones) available which would take longer to setup and obtain the results. The model also needs to meet the requirements of the authority and the practitioner. Each role has different requirements for the model described as follows:

<u>The Authorities' needs are:</u>

- to understand (at a high-level) the behaviours the model can emulate, in order to make a judgement about the validity of the model. If they are interested and/or experienced in modelling, they would also like an understanding of the model parameters.

- results in a variety of formats: these include longitudinal charts and graphs for reports and easy assessment of station operational functioning.

The practitioner's requirements are:

- ease of use: the package should be straightforward to use and user interfaces (UI) should be intuitive. Input and output data should be read and written to appropriate locations and in an easy-to-manipulate format.
- a clear understanding of parameters: i.e. parameters should have some resemblance to the real world. Ideally, it should also be clear what the intended effects of each parameter are, if changed in isolation.
- the ability to modify parameters quickly and easily: again, the UI should enable parameters to be changed easily. It should not take long to make changes to several parameters to set up a new scenario.

Scale is also a key factor in choosing an approach. This includes both the number of platforms / railway lines to be available to the user in the model as well as the size of the environment and the detail required. The choice of the scale of the model is also related to the type and details of the outputs.The aim of the SP-model is to be a support tool for all stages of the design process (from the early planning stage to detailed design). In the early planning stages, the infrastructure is only roughly known, so the design is only assessed at a "*first-order*" level, which is the optimum application level for the SP-model. At the end of the design process, very detailed designs are available, allowing for more detailed inputs into the SP-model in order to assess the designs more accurately should microscopic modelling not be considered. The model should therefore be sufficiently robust to operate on different levels of input detail.

The results of the SP-model have to be reliable and accurate for the purpose and level of design that it serves and this will be tested in Chapter 6 when the model is assessed against two microscopically modelled case study stations. Since the model includes various assumptions and processes, it is important to mention that the model is only as accurate as the space-time-volume matrix method allows it to be and accuracy must also be considered in the context of user friendliness and ease of use. The SP-model application environment is unfortunately very particular to overhead concourse type facilities and, for this model version, cannot be applied to stations with significant variation to this layout theme.

5.2.2 SP-Model Structure

The SP-model can be categorised into three components viz. Input, Processing and Output components as shown in Figure 5.1. The Input component is the only component that allows for user input and here the user is able to define train types, edit the default parameters, and input the situational input and train schedule data. The user is able to edit the default parameters (described later in Section 5.3) which have been based on the empirical data gathered in this research or load and save their own desired default settings for future use, particularly if the user has input values that are more appropriate to the situation being modelled.

The situational input refers specifically to the station infrastructure dimensions, which includes the geometry of all station infrastructure items. Passenger volumes and train schedules are input into the train schedule worksheet. Walking speed distributions, boarding and alighting rates, Passenger arrival rates (*PAR*) and other generic settings are inputted in the Default Parameters worksheet.

The calculation engine within the Processing component consists of a series of hidden worksheets that execute the calculation of the space-time-volume matrices for each of the infrastructure components. Note that although the calculation engine is not macro driven and executes automatically, certain output sheets necessitate user input (e.g. user selection of platform no. and stairs) which are macro driven.

Essentially, the model calculates the travel (walking) times of pedestrians at the start (source) node to the next (sink) node along a uniform section of infrastructure (e.g. stairs) according to the appropriate walking speed histogram defined in the default parameters. These times are then modified according to the prevailing density using the default fundamental macroscopic relationships until all pedestrians have entered and exited the particular infrastructure section.

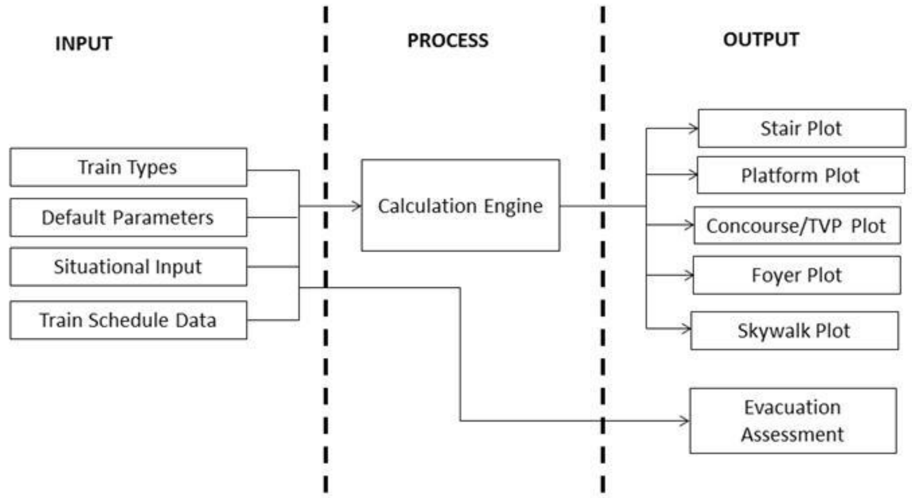


Figure 5.1: SP-model structure

It is intended that the user only make changes to the worksheets of the Input component which describe the default and input conditions that are to be modelled and then extract the required results from the specific output sheets viz. Stair plot, Platform plot etc. The Evacuation assessment output sheet does not require the space-time-volume matrix calculation and can be viewed immediately after the necessary input is provided.

5.2.3 SP-Model Inputs

In Figure 5.1, four categories of input have been distinguished, namely *Train types*, *Default Parameters Situational Input* and *Train Schedule Data.*

The *Train types* worksheet provides the user the opportunity to define up to two train types which the user can select from a set of 12 user-defined train coaches/motor coaches. The model allows for a maximum of 14 coaches per train including the motor-coaches. Note that both boarding and alighting passenger volumes are assigned and distributed according to coach capacity, which the user is allowed to change in the makeup of the train e.g. front and aft motor coaches, metro-plus and metro coaches incorporating the different capacities of the metro coaches might result in a train with a varied passenger volume per coach. It is also important to correctly input the number of doors per coach side as this also affects the boarding and alighting time for the passengers and occupants respectively. Coach lengths also contribute to the ultimate geographic location of each of the coaches with respect to platform staircases.

The *Default Parameters* worksheet provides five sheets of default inputs. Whilst this worksheet is considered an input worksheet, the input parameters are populated with default values obtained from the empirical data collected as part of the primary research. Accordingly, the user may wish to accept the default parameters if the situation context is similar to the station environment observed in this study. Alternatively, further details of the default parameters is described in Section 5.3 below.

The SP-model needs to be versatile enough to model different scenarios easily. This is because the planning horizon of station designs may differ, i.e. designs of new facilities have to be assessed for longer term horizons (twenty to fifty years), whereas during the restructuring of a facility, the pedestrian comfort level needs to be assessed in terms of current conditions. The SP-model allows this by allowing user defined scenarios to be entered and saved from the *Desktop* worksheet. Each of the possible five scenarios (A through to E) consists of its own unique default parameters, situational input and train schedule data.

The *Situational Input* worksheet contains the dimensions of the station facility layout. This includes the dimensioning of different types of infrastructure as indicated in the worksheets (e.g. station layout details, platform stair details, concourse details, skywalk details, platform emergency details, foyer details etc.), as well as the identification of the baseline for the geographic orientation of all station infrastructure items. The model allows up to maximum of four staircases per platform.

All the input parameters required for model operation are defined in sketch format provided in the *Parameter* worksheet. The model allows for asymmetrical concourse layouts with partial concourses that do not extend over all the lines. The concourse and foyer width and length dimensions also serve as the measurement area (MA) for the calculation of the density parameter and can be manipulated or approximated for odd shape concourses if necessary.

The *Train Schedule* worksheet provides the user the opportunity to define up to 20 trains arriving at the station along selected lines alongside platforms. The model allows for up to a maximum of ten railway lines alongside a maximum of six platforms. The direction of train travel is a further important input, particularly when the concourse and staircases are not centrally located on platforms. Note that stopped trains are modelled such that train centres align exactly with platform centres. Whilst on-board passengers do not use the station facility during normal operation times, these passengers need to be considered for the evacuation analysis and are therefore considered an important aspect. On-board volumes also contribute to the overall coach capacity and, in the last column of the spreadsheet, the capacity of the entire train is checked against the passenger demand input by the user. The user is warned of an over-capacity condition if it does occur, but this condition does not prevent the SP-model from running.

Pedestrian demand is input solely as train boarding and alighting passengers. The origins and destinations of the boarding and alighting passengers respectively are input from/to side "*X*" or side "*Y*" of the skywalks as defined in the *Train schedule* worksheet. The quantitative proportions of passengers arriving-from or departing-to the various sides of the skywalks is input under "*Skywalk Details*" in the *Situational Input* worksheet.

The bottom half of the *Train Schedule* worksheet provides a useful graphic representation of the input train schedule showing colour-coded train travel directions, line of operation and time of arrival. The two vertical lines on the plot indicate the peak 15-min operation of the station used exclusively for evacuation analysis. The graphic also provides the benchmark definition of the train trip origin and destination sides (viz. Side "*A*" or "*B*") as well as the lateral spatial definition viz. Side "*X*" or "*Y*". It is important that all inputs are correct relative to these spatial definitions.

5.2.4 The Mesoscopic Method for Tracking Pedestrian Movements

The proposed SP-model for station modelling builds upon the principles of an earlier mesoscopic XML/Java model by Hanisch *et al*. (2003) and Tolujew and Alcalá, (2004). A limitation of their models however, is the inability to model overcrowded situations and determine spatial requirements and/or provide LOS outputs.

Pedestrian variables are calculated for every one second interval and the locality of persons are mapped in the model for pedestrian groups and stored in variable 3-dimensional space-time-volume (STV) matrices. STV matrices comprise of a time component (as the matrix column headers), a walking speed histogram (as the matrix row headers) and the number of pedestrians as the matrix cell values.

In the SP-model, the movement of pedestrians is modelled using infrastructure components (IC's), which are bi-directional pathway connections between two points in space. Infrastructure components are always bound at the two end points by either a source or a sink as defined in Table 5.1.

Table 5.1: Basic components of the SP-model

Component	Function	Example
Source	Fills the model IC with pedestrians.	Arriving/alighting passengers
Sink	Removes pedestrians from the model IC.	Departing/boarding passengers
Infrastructure component (IC)	Models the horizontal and vertical distances between sources and sinks. Pedestrians occupy IC space for as long as they take to cover the walking distance.	Platforms, staircases, concourse, foyer and skywalks

The infrastructure component (IC) is characterized by a length and width component of the specific infrastructure type being assessed (e.g. staircases). All pedestrians at sources are introduced on the IC according to the end state of the STV matrix determined for the previous IC. For example, the end-state STV matrix for movement going up stairs (i.e. at the top of the stairs) would become the start-state STV matrix for the concourse assessment (also at the top of the stairs).

The individuals within the pedestrian group are assigned a walking speed according to a user-defined walking speed distribution which allows the time to cover the length of the IC to be calculated. The end state STV matrix is then updated with the new time for the pedestrian group associated with the particular walking speed; and the process is repeated for all station pathways IC's.

A simple hypothetical example to describe the STV method in which a group of passengers is assessed on a platform IC is explained below. The assessment consists of a simple sum of logical passenger-movement groups. In the example shown in Figure 5.2, the train arrival time is assumed to occur at time t = 500 sec. The two logical passenger-movement groups to be considered are alighting passengers (A) and boarding passengers (B).

In systems where the inflow and outflow of person quantities are caused by means of transportation, these processes can best be described in terms of logical groups. Figure 5.2 show the four processes that can occur on a platform IC between the coach door exits and the base of the staircase. Note that whilst coaches may have several doors, for the purposes of determining walking distances per coach in the model, it is assumed that all alighting "*occurs*" at the centre of the coach. The four quantitative processes include alighting pax at the coach door (A_c), boarding pax at the coach door (B_c), alighting pax arriving at the staircase base (A_s) and boarding pax arriving at the staircase base (B_s). In the case of this platform IC, processes B_s and A_c are considered as pedestrian sources and A_s and B_c as pedestrian sinks.

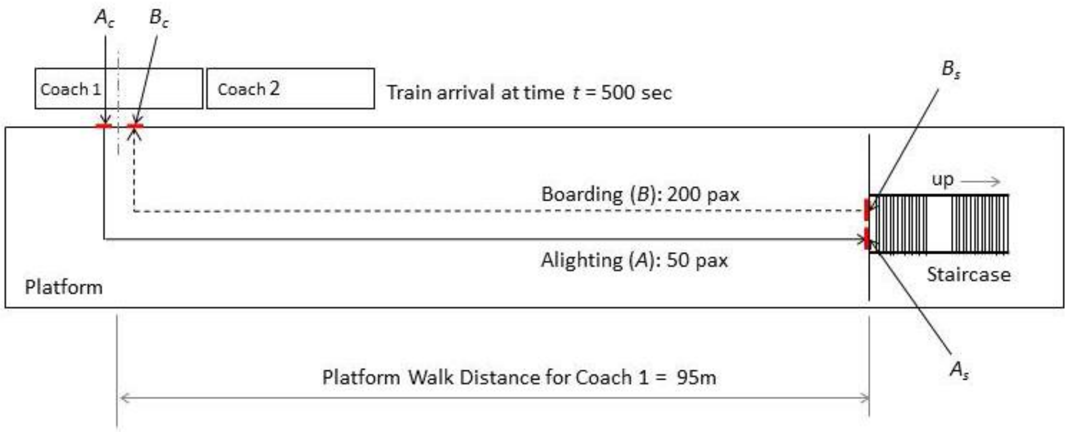


Figure 5.2: Example of train passenger logical groups on a platform IC

The model of behaviour shown in Figure 5.3 for the four logical groups is simple but not trivial. The graph shows boarding pax (B_s) stepping onto the platform (at the base of the staircase), starting at t = 200 sec up until the train arrives at t = 500 sec. The example shown assumes a 2 sec/pax boarding and alighting rate which, with a 2-door coach, means that a single passenger alights or boards every second per coach as shown by the linear boarding and alighting processes, viz. B_c and A_c at the coach door respectively.

Immediately after train arrival at t = 500 sec, alighting occurs, viz. process A_c which occurs before the boarding process, viz. process B_c. As described in Subsection 4.5.1, empirical evidence shows that the boarding process follows sequentially after the alighting process. Once the alighting passengers (A_c) have disembarked, they then need to cover the 95 m length of the platform to the base of the stairs, distributed according to a walking speed histogram. The cumulative number of passengers calculated to reach the base of the stairs is calculated every second and is plotted as process A_s in the graph.

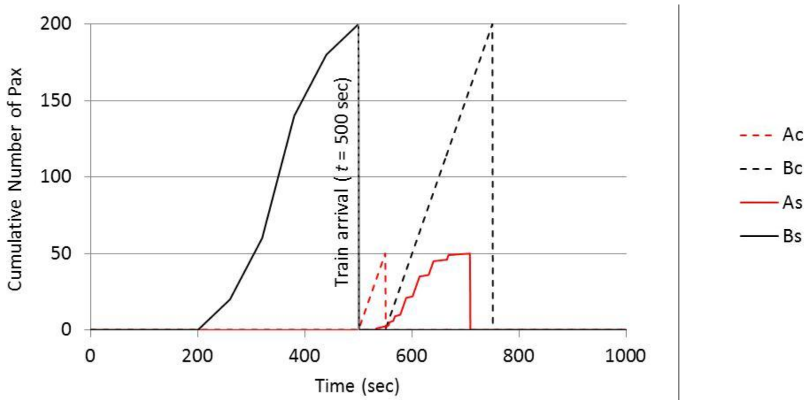


Figure 5.3: Cumulative passenger quantities for four logical processes on a platform IC

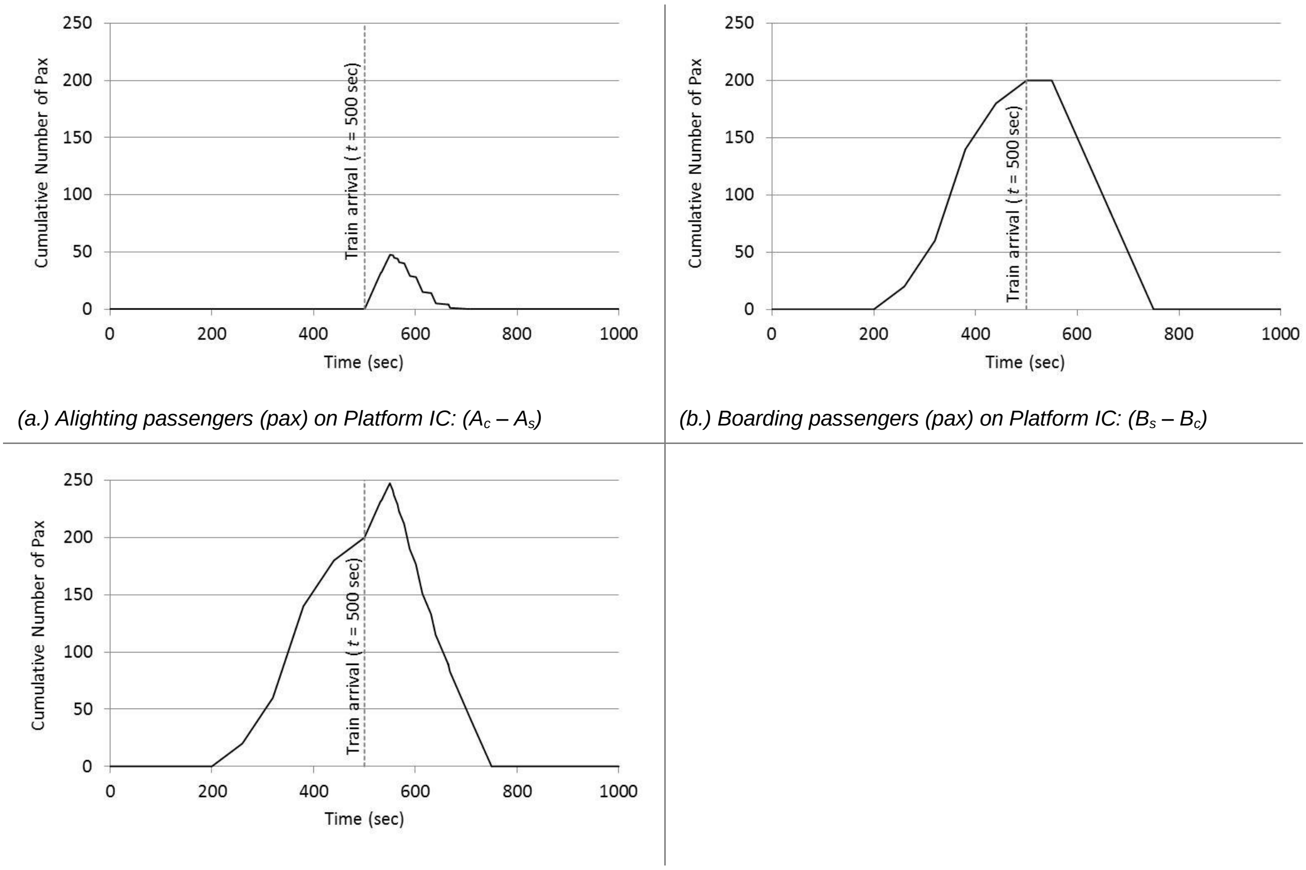
The characteristic of the model process is through the use of cumulative pedestrian quantities as dynamic indicators as shown in Figure 5.4. It has already been demonstrated by Tolujew (2003) that these dynamic indicators can be used as operands in arithmetic and algebraic operations. Figure 5.4 illustrates the operation, which calculates the number of pedestrians on the platform IC during the entire duration of the process. The pedestrian (volume) dynamic on the platform IC shown in Figure 5.4 (*c.*) is a precise result directly inferred from the specified processes A_c, A_s, B_s and B_c.

The quantity of alighting passengers on the platform storage area at the end of the *k*-th time step is:

$$Aliging\ pax\ on\ platform\ IC = \sum_{t=0}^{k}[A_c(t) - A_s(t)] \ldots \text{ refer to Figure 5.4 (}a.\text{)} \qquad [5.1]$$

and the quantity of boarding passengers on the platform IC at the end of the *k*-th time step is:

$$Boarding\ pax\ on\ platform\ IC = \sum_{t=0}^{k}[B_s(t) - B_c(t)] \ldots \text{ refer to Figure 5.4 (}b.\text{)} \qquad [5.2]$$



(a.) Alighting passengers (pax) on Platform IC: ($A_c - A_s$)

(b.) Boarding passengers (pax) on Platform IC: ($B_s - B_c$)

(c.)Total passengers (pax) on Platform IC: ($A_c - A_s$)+ ($B_s - B_c$)

Figure 5.4: Calculation of the entire passenger volume quantity on the platform IC

The quantity of pedestrians (Number of Pax) on the platform IC, dynamically calculated over the 1000 second simulation, is shown in Figure 5.4 and is the sum of equations [5.1] and [5.2].

Whilst the process appears simple for a single train coach as explained in the hypothetical example above, the calculation becomes particularly lengthy for passenger movement from multiple coach trains, simultaneous train arrivals on the same platform or for train arrivals at short headways where alighting passengers from the first train have not yet cleared the platform before alighting occurs from the second train. This is the fundamental basis of the STV calculation process and is applied to all other station infrastructure components (IC's).

5.2.5 The Space-Time-Volume (STV) Matrix Algorithm

The SP-model calculates the spatial location of boarding and alighting pedestrian groups using separate algorithmic routines as shown in Figure 5.5. This is to account for the different movement dynamic between these two groups of passengers, i.e. alighting passengers offer a variable rate of flow from a specific point in time (viz. train arrival) whilst boarding involves waiting time on the platforms and variable arrival rates over a longer period of time. This subsection provides more detail on the STV matrix algorithm used to calculate the geographic location of first the alighting group and then the boarding group of pedestrians on a station platform in order to calculate the longitudinal LOS. The same technique is applied and repeated to all the station infrastructure types (viz. stairs, concourse, foyers etc.) for determining the longitudinal LOS profiles.

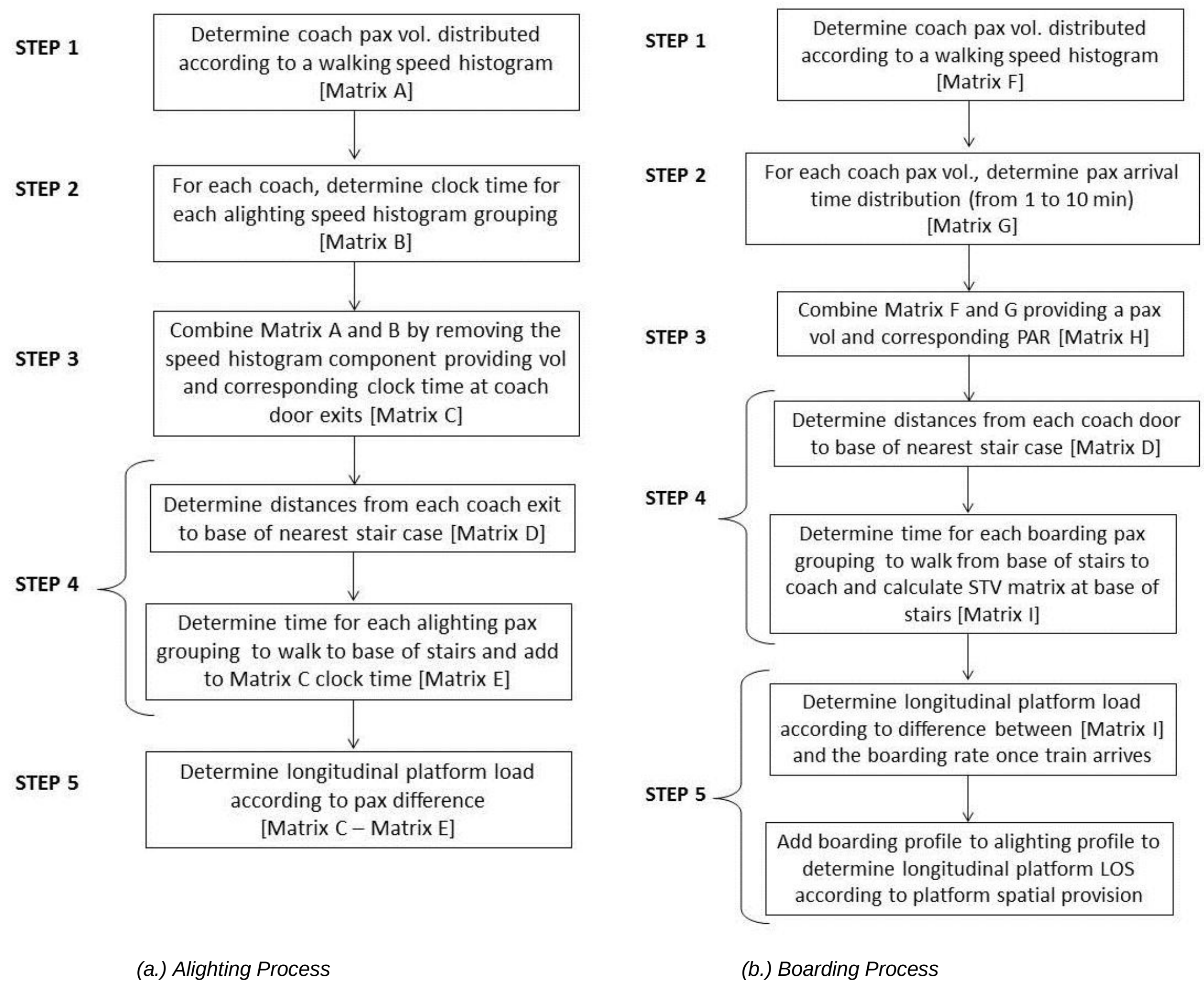


Figure 5.5: Flowchart for determining Boarding and Alighting STV matrices (for Platform/s only)

Alighting Group:

The first step, for this group, is the calculation of the Space-Time-Volume (STV) matrix for the alighting process at each of the train coach doors, which starts to occur from the moment the arriving train stops according to the default passenger alighting rate.

Step 1: For each coach in the train set, alighting passengers are allocated a platform walking speed, distributed according to the platform alighting walking speed histogram. This then assigns a walking speed to a group of alighting passengers per coach *n* as shown below in matrix [A].

Coach No.'s

Platform Alighting Speed Histogram (m/s)

$$\begin{array}{c|cccc} & 1 & 2 & \ldots & 14 \\ \hline 0.2 & a_1 & a_2 & \cdots & a_{14} \\ 0.4 & b_1 & b_2 & & \vdots \\ \vdots & \vdots & & \ddots & \\ 3.0 & o_1 & \cdots & & o_{14} \end{array} \qquad \ldots\ldots\ldots\ldots [A]$$

where a_n, b_n … o_n are passenger volumes; the subscript *n* represents the associated coach number and where *a*, *b* … *o* is associated with one of the 15 histogram walking speeds from 0.2 to 3.0 m/s.

Step 2: For each coach in the train set, the alighting clock time of the groups of alighting passengers identified in the previous step is shown in matrix [B] below.

Coach No.'s

Platform Alighting Speed Histogram (m/s)

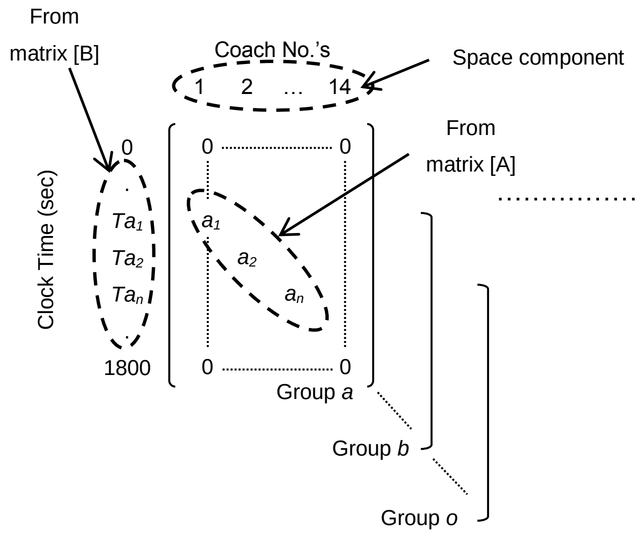
$$\begin{array}{c|cccc} & 1 & 2 & \ldots & 14 \\ \hline 0.2 & Ta_1 & Ta_2 & \cdots & Ta_{14} \\ 0.4 & Tb_1 & Tb_2 & & \vdots \\ \vdots & \vdots & & \ddots & \\ 3.0 & To_1 & \cdots & & To_{14} \end{array} \qquad \ldots\ldots\ldots\ldots [B]$$

where Ta_n, Tb_n … To_n are the coach alighting clock times (in sec) according to the alighting rates, the subscript *n* represents the associated coach number and the prefix lettering (viz. *a*, *b* … *o*) is associated with one of the 15 histogram walking speeds. By way of example, if o_1 = 4 passengers in Matrix [A], and the alighting rate is 0.5 sec/pax, then 2 passengers would alight every second and hence the o_1 alighting clock time associated with o_1 would calculate to To_1 = 2 seconds, in Matrix [B], assuming a train arrival at clock time *t* = 0.

As indicated in Section 5.2.3, passenger volumes are distributed according to coach capacity, which the user is allowed to change in the makeup of the train. This might result in a train with a varied passenger volume per coach which would then calculate the alighting clock times of walking group *a, b …o* to be different for all the coaches.

In this calculation process, it is assumed that persons with faster walking speeds alight first and those walking slower alight last. In other words, clock times always increase in the direction from passenger groups o_n to a_n.

Step 3: For each of the passenger volume groups (a_n, b_n … o_n) identified in matrix [A] (i.e. Step 1), there is a corresponding alighting clock time (Ta_n, Tb_n … To_n) as determined in matrix [B] (i.e. Step 2). These two components allow for the development of the time-volume matrix shown in matrix [C'] for each of the walking speed groups (*a through* to *o*). The columns of the calculated time-volume matrix is for a particular point or location in space, in this instance the coach door exits and the time-volume matrix is thus referred to as a space-time-volume (STV) matrix. The dimensions associated with the space component is defined in matrix [D] below. The STV matrix at each of the coach door exits is represented as follows:



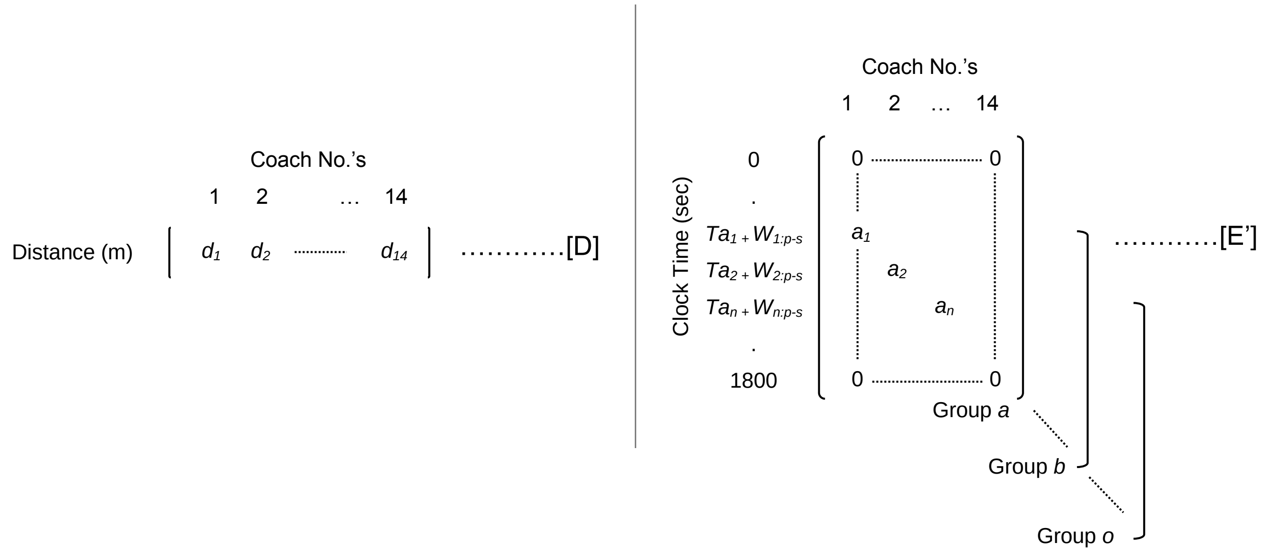
……………………………………………………………………….[C']

where Ta_n represents the particular clock time from matrix [B] that is allocated to the group of passengers from matrix [A]. The process is repeated for all alighting clock times (Ta_1 to Ta_{14}, Tb_1 to Tb_{14} … To_1 to To_{14}) until matrix [C'] contains all the corresponding passenger group volumes (a_1 to a_{14}, b_1 to b_{14} … o_1 to o_{14}).

Note that for the purposes of matrix demonstration, it is assumed that clock times $Ta_1 < Ta_2 < Ta_n$, which is not always the case and is largely dependent on the coach passenger distribution. If the passenger volumes are distributed uniformly across all coaches then $Ta_1 = Ta_2 = Ta_n$. The diagonal placement of a_1, a_2 to a_n shown in matrix [C'] above is therefore intentional to indicate that clock times might not necessarily be equal (because of the possibility of a non-uniform passenger coach load as stated in Step 2 above).

It is then necessary to combine all walking speed group matrices *a* through to *o* into a single [15 x 14] matrix (note that if different walking speed groups have passenger volumes for the same clock time, these cell values are then added together). Finally, in order to obtain the cumulative passenger volume alighting on the platforms for the entire train at the coach door screenline, the matrix entries of matrix [C'] for all coaches (viz. columns) are then added cumulatively from time $t = 0$ to $t = 1800$ to achieve a [15 x 1] matrix [C].

Step 4: From the matrix [C'] developed above, each passenger group (volume) matrix entry from [a_1 to a_{14}] to [o_1 to o_{14}] is associated with a coach exit clock time [Ta_1 to Ta_{14}] and [To_1 to To_{14}] respectively. Together with the distance matrix [D] shown below (i.e. the distance from the respective coach door exits to the stairs), the space-time-volume matrix at the base of the staircases can be calculated for each coach for each alighting passenger group; resulting in matrix [E'] as shown below. Essentially, matrix [E'] is the same as matrix [C'] except with the walking time to the base of the stairs $W_{n:p\text{-}s}$ from the respective coach doors added to the alighting clock time Ta_n.



where $[Ta_n+W_{n:p\text{-}s}]$ is the clock time at the base of the stairs and is the sum of the particular alighting clock time (Ta_n) at the coach door exits plus the walking time from the coach exits to the base of the stairs $W_{p\text{-}s}$. Since pedestrian group a_1 (i.e. from coach 1) is associated with a walking speed of 0.2 m/s, then:

$$W_{1:\,p-s} = \frac{d_1}{0.2}$$

As with the development of matrix [C], all walking speed group matrices *a* through to *o* of matrix [E'] are combined into a single [15 x 14] matrix, of which the cell entries are accumulated from time t = 0 to t = 1800 to achieve a [15 x 1] matrix [E].

Step 5: Matrix [E] provides the cumulative STV matrix at the base of the stairs whilst matrix [C] provides the cumulative STV matrix at the coach door exits. The difference between these two matrices viz. matrix [C] – matrix [E] then provides the number of alighting passengers on the platform on a time (longitudinal) scale.

Step 6: In order to determine the spatial assessment of the staircases, for each coach in the train set, alighting passengers [a_n to o_n] are separately allocated a staircase walking speed according to the ascending staircase walking speed histogram.

Step 7: Since the walking speed histograms are different for level terrain than for staircases, a process needs to be introduced which "assigns" the walking speed distribution of the platform pedestrians to an appropriate stair ascending speed. This process is termed "histogram mapping" and is explained in detail in Subsection 5.3.5.

In summary, histogram mapping[28] allocates the slowest walking pedestrians on the platform to the slowest stair ascending speeds and repeating the process until the entire platform histogram is mapped to a stair ascending histogram. The process is repeated for all 14 coaches so that all passengers are accounted for.

Step 8: For each coach and passenger group, we have already calculated the arrival clock time at the base of the stairs viz. matrix [E]. Together with the horizontal stair distance matrix, the clock time of each coach and passenger group is then calculated and a new STV matrix can be calculated at the top of the stairs. As with the platform LOS calculation (viz. Steps 4 and 5) the difference between matrices provides the longitudinal number of pedestrians on the staircases for LOS evaluation.

Step 9: To determine the STV matrix at the turnstile battery, each passenger group (at the top of the stairs) now again needs to be assigned to a level walking speed histogram. Repeating the histogram mapping process used in Step 7 is used to achieve this. Together with the walking distance from the top of the stairs to the turnstiles, the STV matrix at the turnstile battery can be calculated and again the concourse LOS evaluation can be calculated based on the matrix difference.

Steps 10 and 11: The same process is repeated to obtain the STV matrix at the foyer entrance in order to calculate the foyer LOS.

Boarding Group:

The STV matrix calculations for the boarding passenger group is more complex due to the variable Passenger Arrival Rates (*PAR*) prior to train arrival with the accumulation of waiting passengers on the platforms. Since boarding occurs after alighting, the boarding start and end times can be calculated based on the default boarding rates.

Step 1: For each coach in the train set, boarding passengers per coach are allocated a walking speed distributed according to the platform boarding walking speed histogram. This then assigns a walking speed to a group of boarding passengers viz. a_n, b_n to o_n per coach n as shown below in matrix [F].

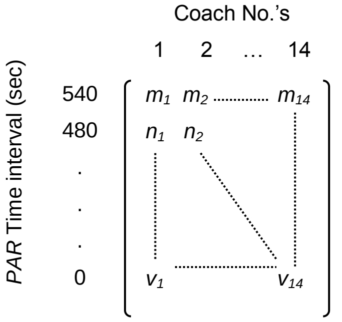
Coach No.'s

Platform Boarding Speed Histogram (m/s)

$$\begin{array}{c} \\ 0.2 \\ 0.4 \\ \cdot \\ \cdot \\ \cdot \\ 3.0 \end{array} \begin{array}{c} \begin{array}{cccc} 1 & 2 & \ldots & 14 \end{array} \\ \begin{bmatrix} a_1 & a_2 & \cdots & a_{14} \\ b_1 & b_2 & & \vdots \\ \vdots & & \ddots & \\ o_1 & & \cdots & o_{14} \end{bmatrix} \end{array} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[F]$$

where a_n, b_n … o_n are passenger volumes; the subscript n representing the coach number and the prefix lettering (viz. a, b … o) is associated with one of the 15 histogram platform walking speeds from 0.2 to 3.0 m/s.

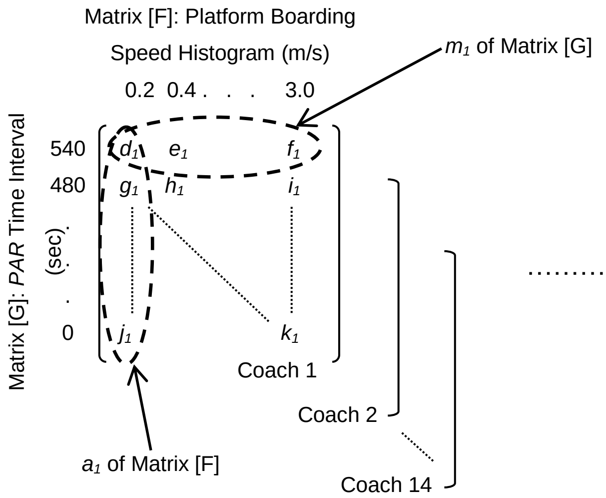
Step 2: For each coach in the train set, passenger volumes arriving onto the platform need to be calculated according to the passenger arrival rate (*PAR)* distribution as shown below. This then assigns a volume of passengers viz. (m_1, n_1 …v_1) per coach according to the *PAR* time distribution as shown in matrix [G].



……………………………………………………………………..[G]

where m_n, n_n … v_n are passenger volumes; the subscript *n* represents the coach number and the prefix lettering (viz. *m*, *n* … *v*) is associated with one of the ten minute *PAR* intervals.

Step 3: For each coach in the train set, matrix [F] provides the passenger volume per platform boarding speed group viz. a_1, b_1 ….o_1 for coach 1, a_2, b_2 ….o_2 for coach 2 and so on. Likewise, matrix [G] provides the boarding passenger volume per time interval as per the *PAR* distribution. This provides a [F x G] matrix group of passengers that needs to follow a balancing process. The balancing process is shown in matrix [H] below where $\Sigma(d_n + e_n + \ldots f_n) = m_n$ of matrix [G] and $\Sigma(d_n + g_n + \ldots j_n) = a_n$ of matrix [F] for coach *n*. The process is repeated for all 14 coaches so that all passengers are accounted for.



……………………………………………………………..[H]

Step 4: Matrix [H] provides an arrival time range of up to ten minutes prior to train arrival, together with the associated passenger volume and corresponding walking speed of those passengers. This allows for the calculation of the STV matrix (identified as matrix [I] *not shown*) at the base of the staircases using the same distance matrix defined in matrix [D] except in this case by deducting the calculated walk time and *PAR* time from the train arrival clock time to determine the pedestrian group clock times. Matrix [I] is a [15 x 1] matrix with cumulative passengers arriving on the platform at the stair base screenline from time $t = 0$ to $t = 1800$.

Step 5: Determine the longitudinal platform load according to difference between matrix [I] and the cumulative passenger boarding rate once the train arrives (all passengers board at the same rate) which then provides the number of boarding passengers on the platform on a time (longitudinal) scale. This passenger volume is then added to the alighting passenger profile to determine spatial LOS depending on the chosen platform size.

Step 6: In the case of boarding passengers, the mesoscopic groups are defined in matrix [H] by the *PAR* distribution at the first (column) level and by the platform boarding histogram at the second (row) level of the matrix. In Step 4, the calculation of the STV matrix at the base of the staircase (matrix [I]) was determined by deducting the calculated walk time and *PAR* time from the train arrival clock time. In order to calculate the STV matrix at the top of the stairs, histogram mapping from the stair descending speed histogram to the platform boarding speed histogram is necessary to replace the second (row) level of matrix [H] with the appropriate speed histogram for the stair infrastructure.

Step 7: In order to calculate the STV matrices at the TVP battery, foyer entrance and at the skywalks themselves, histogram mapping from the skywalk speed histogram to the platform boarding speed histogram is necessary to replace the second (row) level of matrix [H] with the appropriate speed histogram for level (skywalk) infrastructure. The various distance matrices for each of the particular infrastructure component (IC) sections is then used to calculate the walking time and ultimately the clock time of the various STV matrices.

Comment on Stair Route Assignment:

For each coach door exit, the inputs require a distance to each of the staircases as per matrix [D]. In the development of the passenger STV matrices, boarding or alighting passengers from a particular coach are automatically allocated the closest staircase. In the algorithm, each coach door is thus allocated or assigned a particular staircase in order to later assign passenger volumes to those particular staircases.

Development of Longitudinal plots:

The algorithmic steps described above for both the boarding and alighting process have each produced their own individual STV matrices. Towards the development of the longitudinal output plots, the STV matrices of each of the separate (boarding and alighting) processes are added together. In the case of determining the staircase volumes, the columns of STV matrices of coaches assigned to the closest stair are added together. This then provides a STV matrix (providing longitudinal passenger volume data) at either the base or the top of the stairs. Note that STV matrices are developed at each end of the infrastructure component (IC) as defined in Subsection 5.2.5, i.e. at the sources and sinks and not for the IC itself. The number of pedestrians on the staircase (and other infrastructure components) thus becomes a simple mathematical calculation based on subtracting the number of persons exiting the stair IC from those entering the stair IC area as described in Subsection 5.2.5 and shown graphically in Figures 5.3 and 5.4. The same method is used to determine passenger densities on the concourse, foyer IC's etc.

In terms of determining longitudinal flow rates on IC's, the flow rate calculation is based on the addition of matrix values over a one-minute interval at either end of the IC assessment area (e.g. at the top and bottom of the stairs). The longitudinal flow rate plot then uses the average of these two values over time as the flow rate value.

5.2.6 SP-Model Performance Indicators (Outputs)

It is important to realise that the level-of-service (LOS) output is longitudinal by nature (i.e. time dependant) as flows and density vary over time depending on the demand dynamic of pedestrians. It is therefore preferable that LOS criteria should be identified for a specific time interval ideally over small intervals for the assessment period. As indicated in Subsection 2.1.4, an average LOS calculated over the peak 15-minute period is not an acceptable means for station infrastructure assessment. This is because the concourse (or any station area being assessed) could be empty during one minute but relatively crowded during the next because of a train arrival.

For the purposes of the SP-model and due to the nature of the STV calculation process, LOS output has therefore been based on calculations performed for every second but averaged over 60-second intervals for the duration of the peak 15-min period.

The SP-model provides longitudinal flow rate and/or density output criteria for the following infrastructure types:

- *Platforms*: Only densities over the 1800 sec analysis period are plotted, since flow rate criteria is entirely dependent on where the "*assessment*" flow line (or screenline) is placed relative to the train. Densities are plotted every second over the (train) length of the platform.
- *Staircases*: Density is plotted as well as flow rate over the 1800 sec analysis period. Density is calculated over the entire horizontal length of the staircase and the flow rate is determined at the middle of the staircase. For the density criteria, results are displayed as a running average over 60-second intervals whilst the flow rate plotted over 60-second intervals.
- *Concourse*: Density is plotted over a 1800 sec analysis period. Results are displayed as a running average over 60-second intervals over the entire concourse area.
- *TVP*: Queuing densities are plotted over the 1800 sec analysis period calculated from the density vs. *v/c* relationship described in further detail in Subsection 5.3.6. Results are displayed as a running average over 60-second intervals. *Foyer*: Longitudinal density is plotted over a 1800 sec analysis period. Results are displayed as a running average over 60-second intervals at the position of the TVP battery.
- *Foyer Entrance*: Flow rate is plotted for the 1800 sec analysis period. Results are displayed as points representing flow rate data over 60-second intervals over the entire foyer area.
- *Skywalks*: Flow rate is plotted over the 1800 sec analysis period for both sides of the skywalk. The location of the screenline on the skywalk for determining the flow rate values is important and is defined as the "*Flow rate evaluation distance*" (*FRED*). The larger *FRED* is, the more dispersed the flow rate becomes.
- *Evacuation*: The design of a station facility not only needs to be assessed under normal operational conditions, but also in extreme conditions such as an evacuation event. Adequacy of existing and emergency infrastructure provided for these eventualities is checked as a matter of safety in the SP-model (but is not modelled). The evacuation output shows two pages of output. The first page shows the individual platform loads per train arrival as well as the peak 15-min period for evacuation assessment also defined as the "*failure period*"[21] according to the NFPA 130 definition. The lower graph

shows the calculated design platform "*occupant loads*"[40] based on the maximum train load for any line within the 15-min "*failure period*". Page 2 of the evacuation assessment follows the standard NFPA 130 "*Exiting Analysis*" template (NFPA 130 2003) that:

1. Tests that the design platform "*occupant load*" can evacuate from the platform in four minutes or less, and,

2. Tests that the platform "*occupant load*" from the most remote point on the platform can be evacuated to a point of safety in six minutes or less.

5.2.7 SP-Model Assumptions and Limitations

Assumptions, limitations or clarifications related to the SP-model are indicated in the following list:

- It is assumed that trains stop such that train centres are aligned with platform centres.
- Train passenger boarding and alighting loads are distributed across coaches according to total coach passenger capacity.
- It is assumed that passengers with higher walk speeds will alight the train first, followed by slower pedestrians.
- A maximum of 14 coaches per train set is allowed in this model version.
- A maximum of 20 trains can be modelled on 10 train lines (up to 6 platforms) within a 30 min assessment period only.
- A maximum Passenger Arrival Period of 10 min is allowed only.
- Faster walking passengers are associated with later *PAR* times, just prior to train departure.
- Only staircases/ramps are considered for passenger movement from concourse to platforms and vice versa. Lifts and escalators are not considered in the model.
- The baseline is defined to be perpendicular to the railway lines and located at one end of the platforms as defined in the SP-model user manual attached in Appendix L.
- Staircase densities are calculated over the entire horizontal length of the stairs.
- Effective platform width is the platform width (from the platform edge), clear of any obstructions available for pedestrian mobility as defined in Figure 6 of the SP-model user manual attached in Appendix L.
- This version of the model allows full alighting to occur prior to boarding and does not allow for simultaneous boarding and alighting.
- Platform density is calculated over a user-defined measurement area length (*MAL*) over the platform and the effective platform width.
- A platform can only have one or two railway lines/tracks associated with it. The SP-model does not restrict permitted input.
- The horizontal length of the stairs is considered the same for all platforms as it is assumed that the concourse is the same height for all platforms.

- In terms of walking histogram/s user input, all walking speeds faster than 3 m/s are to be allocated to the 3 m/s dataset. In other words, walking speeds in excess of 3 m/s cannot be specified.
- Histogram mapping is complex to program and needs to be done manually in this model version. Histogram mapping is explained in more detail in Subsection 5.3.5.
- In this model version, stair usage per platform is uniformly distributed and utilised.
- The algorithm calculating the stair flow rate is based on the average flow rates at the top and bottom of stairs.
- Turnstiles/ TVP's are assumed to be functionally bi-directional.
- The model includes the impact of street-to-street pedestrian volumes on skywalk performance measurements.
- The model does not consider the impact of ticket sales on station operation, nor the impact of ablution facility use at the concourse level.
- The overall passenger boarding and alighting rates determine dwell time, so train dwell time input is not required in the model.

5.3 SP-Model Calibration (Default Parameters)

The following subsections contain a discussion on the default parameter values used in the calibration of the SP-model. Model calibration is the process of extracting, from observations of real pedestrians, the values (or the distributions of values) of the entity parameters and applying these to the default parameters of the model. As indicated by the Rail Safety and Standards Board (2003), if the effects of the variables on any simulation or modelled outcome has not been tested and validated against real behaviour, then the modelling offered can be considered questionable.

Bierlaire, Antonini and Weber (2003) found that there are few models presented in the literature that have been calibrated with real data because data collection for the purpose of observing pedestrian dynamic is particularly difficult, time consuming and expensive. The key challenge in modelling is the validation of the model assumptions on the one hand and verifying the results on the other hand.

According to Kleijnen (1992), verification is referred to as a check whether no mistakes have been made in the implemented algorithms in order to find whether both the model and underlying algorithms work as intended. During the development of the SP-model, verification was achieved by testing each algorithm individually. However, it was impossible to test all the algorithms separately (due to the interdependence of certain algorithms) and therefore some tests evaluated a group of algorithms.

Validation, according to Kleijnen (1992), is described as a check whether the model gives a sufficiently accurate representation of reality. During the validation of a simulation tool or a similar application like the SP-model, predictions from the model should be compared with observations from reality, or, since this is not possible in our case, comparison is made with the results of microscopic modelling. Additional research is to be performed for a comparison of the SP-model results against real pedestrian behaviour.

The assessment of the SP-model has been based on the results of two VISSIM simulation exercises conducted at Century City and Langa Stations in Cape Town, South Africa. Both stations have multiple platforms with overhead concourses and multiple staircases servicing the platforms. Selection of variables for the functionality assessment process includes the comparison of infrastructure density and flow rate longitudinal plots over the entire 30- minute assessment period. Results of this exercise is discussed in Chapter 6.

5.3.1 Boarding and Alighting Details

In Subsection 4.5.4, it was asserted that boarding and alighting times follow a linear approximation with R^2 values of 0.482 and 0.810 for boarding and alighting movements respectively (see Figure 4.69). Both linear functions also had *P*-values of less than 5% making both linear relationships statistically significant. Note that the overall boarding (*BT*) and alighting times (*AT*) indicated in the function/s below are per single coach door only:

$$BT = \alpha_b . B_{pax} + \beta_b$$

and similarly:

$$AT = \alpha_a . A_{pax} + \beta_a$$

where:

BT = Boarding time (sec)

AT = Alighting time (sec)

B_{pax} = Boarding passenger volume

A_{pax} = Alighting passenger volume

α = rate of boarding or alighting with suffixes "*a*" and "*b*" referring to alighting and boarding conditions respectively.

β = initial lost time with suffixes "*a*" and "*b*" referring to alighting and boarding conditions respectively.

Proposed SP-model default values, as obtained from the empirical studies conducted in this research (refer to Subsection 4.5.4) is as follows:

α_b = 0.8745 and β_b = 5.2947

α_a = 0.5011 and β_a = 1.6139

The SP-model models boarding and alighting behaviour according to the same six stages defined by Daamen (2004) as follows:

1. Boarding passengers arrive and wait on the platform for the train to arrive.
2. Arrival of the train.
3. Passengers alight, while boarding passengers queue in front of the doors.
4. Passengers board and leave the platform.
5. Departure of the train.
6. Alighted passengers walk to the platform staircase exits.

5.3.2 Passenger Arrival Rates

The Passenger Arrival Rate (*PAR*) criteria is important since it contributes to the passenger volume and hence density on platforms prior to train arrivals. Usually this is not critical as a quantitative criteria when considered in isolation, but if combined with a scheduled train stop with alighting passengers using the same facility, it may contribute towards triggering unacceptable LOS values for the particular platform assessed.

The proposed *PAR* default values used in the SP-model have been derived from the empirical observations undertaken and discussed in Subsection 4.3.7. Note that the empirical evidence suggests that over 50% of boarding passengers arrive on the platform within two minutes of the train arrival time. We further note that the empirical *PAR* values were obtained from staircase flow observations and so the 50% figure may be unrealistically high since it was observed that many passengers waited for their trains at the concourse level or on the staircase itself. The default SP-model Passenger Arrival Rates (*PAR*) are indicated in Table 5.2.

Table 5.2: SP-model default Passenger Arrival Rates (*PAR*)

Time* (min)	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Pax (%)	29%	22%	17%	12%	8%	5%	3%	2%	1%	1%

**Time period prior to train arrival*

5.3.3 Pedestrian Walking Speed Distribution

The way pedestrians are modelled in the SP-model is largely dependent on the pedestrian walking speed distribution or histogram associated with a particular infrastructure item and/or movement. For example, pedestrians tend to have higher average walking speeds on flat surfaces than when negotiating stairs for instance and the corresponding acceptable density LOS thresholds also vary. Pedestrian movement on staircases is especially important as here the speed distribution is dependent on the direction of travel viz. in either the ascending or descending direction, stair slope and step riser and tread dimensions. Note that pedestrian movement on escalators has not been included in this version of the SP-model.

Table 5.3 provides the default walking speed profiles for the various infrastructure types within the station environment and is based on the empirical observations of this research. Note that reference to the relevant subsection is indicated underneath each infrastructure type for easy reference.

Table 5.3: Default walking speed distribution/s for various station infrastructure types

Walking Speed (m/s)	Platforms (See Subsection 4.3.5)		Stairs* (See Subsection 4.2.3)		Skywalk*[2] (See Subsection 4.2.2)
	Alighting Pax (%)	Boarding Pax (%)	Ascending Pax (%)	Descending Pax (%)	Pax (%)
0.2	-	-	-	-	-
0.4	-	0.1	13.2	20.5	-
0.6	2.0	5.3	68.6	55.3	3.2
0.8	7.9	14.5	11.7	14.2	11.1
1.0	20.0	26.9	3.1	4.6	25.1

Table 5.3: Default walking speed distribution/s for various station infrastructure types

Walking Speed (m/s)	Platforms (See Subsection 4.3.5)		Stairs* (See Subsection 4.2.3)		Skywalk*[2] (See Subsection 4.2.2)
	Alighting Pax (%)	Boarding Pax (%)	Ascending Pax (%)	Descending Pax (%)	Pax (%)
1.2	27.3	28.4	1.2	3.2	30.5
1.4	23.7	17.5	0.5	1.4	17.5
1.6	9.5	5.3	0.8	0.5	6.4
1.8	3.6	0.9	0.6	0.2	2.3
2.0	0.8	0.4	0.2	0.1	1.0
2.2	0.5	-	0.1	-	0.6
2.4	0.5	-	-	-	0.5
2.6	0.6	0.1	-	-	0.5
2.8	0.4	0.1	-	-	0.4
3.0	3.2	0.5	-	-	0.9

**:Note that speeds for staircases are horizontal speeds.*

**[2]:Skywalk speeds incorporate all other flat surface speeds and are therefore applied to foyer and concourse areas.*

Note the high 3.2% frequency of alighting platform passengers walking (or rather running) at the 3.0 m/s category. As already mentioned in Section 4.6, this was found to be often the case as many of the first passengers alighting choose to run ahead of the ensuing alighting crowd to avoid the congestion going up the staircases. The 3.0 m/s group includes all persons running at or above this speed.

5.3.4 Level-of-Service Criteria

The level-of-service thresholds from the *Transit Capacity and Quality of Service Manual* (TRB 1999c) have been used as the default thresholds as indicated in Table 5.4. As already indicated previously, these differ to the thresholds provided in the *HCM 2000* (TRB 2000) specifically to account for pedestrian movements within public transit areas.

Table 5.4: TCQSM Level-of-service criteria; (Source: TRB 1999c)

LOS	Skywalk*	Stairways*	Concourse/Foyer queuing areas	Concourse/Foyer areas
	Flow (pax/m/min)	Flow (pax/m/min)	Space-density (m^2/pax)	Space-density (m^2/pax)
A	< 23	< 16	> 1.2	> 3.3
B	23-33	16-23	0.9-1.2	2.3-3.3
C	33-49	23-33	0.7-0.9	1.4-2.3
D	49-66	33-43	0.3-0.7	0.9-1.4
E	66-82	43-56	0.2-0.3	0.5-0.9
F	> 82	> 56	< 0.2	< 0.5

**Note that the flow rate criteria shown in the table are not adjusted for the LOS-mismatch phenomena discussed in Section 4.4.*

5.3.5 Histogram Mapping

Histogram mapping is a means to map walking speed histograms associated with different infrastructure types to each other. In the SP-model, the start of the STV matrix calculation begins on the platform from the moment the train stops alongside the platform. From this moment, alighting passengers are tracked with positive time intervals through the infrastructure and boarding passengers are conversely backtracked with negative time intervals through the station infrastructure.

For the alighting group of passengers of each coach, passengers are allocated walking speeds according to the default walking speed distribution indicated in Subsection 5.3.3 above. By way of an example, the histogram mapping process of an alighting volume of 100 pax, as shown in Table 5.5, is described as follows:

Firstly, the default platform walking speed distribution is defined into passenger groups as follows: From the platform walking speed histogram shown in Table 5.5, Group 1 is defined as containing two passengers walking at a speed of 0.6 m/s on the platform; Group 2 contains eight passengers walking at a speed of 0.8 m/s, Group 3 contains 20 passengers walking at a speed of 1.0 m/s and so on until Group 10 where 3 passengers walk at 3.0 m/s.

Table 5.5: Histogram mapping example for 100 alighting passengers

Walking Speed (m/s)	Pax Group	Platform Pax (%) (see Table 5.3)	∑ Platform Pax	Histogram-mapping	∑ Stair Pax	Stair Pax (See Table 5.3)
0.2	-	-	-		-	-
0.4	-	-	-		**13**	13
0.6	1	2	2		**82**	69
0.8	2	8	**10**		**94**	12
1.0	3	20	30		**97**	3
1.2	4	27	57		98	1
1.4	5	24	**81**		98	-
1.6	6	10	91		99	1
1.8	7	4	**95**		**100**	1
2.0	8	1	96		-	-
2.2	9	1	97		-	-
2.4	-	-	97		-	-
2.6	-	-	97		-	-
2.8	-	-	**97**		-	-
3.0	10	3	**100**		-	-
Total		100				100

Once this group of alighting passengers reach the stairs, these different walking groups (1 through to 10) need to be assigned a new ascending staircase walking speed. Since the default staircase speed distribution requires 13 pax ascending at 0.4 m/s, it is then necessary to associate both platform groups 1 and 2 with a stair walking speed of 0.4 m/s. In other words, the Group 1 and 2 platform groups with speeds of 0.6 m/s and 0.8 m/s respectively are mapped to a singular stair climbing speed of 0.4 m/s. The process is repeated until the entire distribution is mapped to the other.

The mapping intuitively assumes that the slowest people walking on level ground will also negotiate staircases at a slow speed, which is not an unreasonable assumption. Note that due to the independent walking histograms of the various infrastructure types, an exact match of cumulative passenger distributions is not usually possible or likely but the objective of manual mapping is to attempt to align both cumulative passenger distributions as much as possible. Towards assisting the user in the mapping process, the SP-model provides a percentage cumulative passenger graph for the various infrastructure types to allow the user to visually see the match of the cumulative graphs. The intention is that this process becomes automated in future versions of the SP-model.

The default histogram mapping settings saved with the SP-model has already been optimised for the empirical data observed.

Table 5.6 shows the default histogram mapping settings. Only three histogram mapping scenarios are required viz. Stair (descending) to platform boarding (A → B), skywalk (level surface) to platform boarding (A → C) and skywalk (level surface) to platform alighting (D → E). For the purposes of the SP-model, the skywalk histogram speeds have been applied to both the foyer and concourse level infrastructure areas, and not just the skywalk.

Table 5.6: Default histogram mapping settings

<table>
<tr><th>A</th><th>B</th><th>A</th><th>C</th><th>D</th><th>E</th></tr>
<tr><th>Platform boarding speed (m/s)</th><th>Mapped stair (descending) Speed (m/s)</th><th>Platform boarding speed (m/s)</th><th>Mapped skywalk speed (m/s)</th><th>Platform alighting speed (m/s)</th><th>Mapped skywalk speed (m/s)</th></tr>
<tr><td>0.2</td><td>0.2</td><td>0.2</td><td>0.2</td><td>0.2</td><td>0.2</td></tr>
<tr><td>0.4</td><td rowspan="3">0.4</td><td>0.4</td><td rowspan="3">0.4</td><td>0.4</td><td rowspan="4">0.4</td></tr>
<tr><td>0.6</td><td>0.6</td><td>0.6</td></tr>
<tr><td>0.8</td><td>0.8</td><td>0.8</td></tr>
<tr><td>1.0</td><td rowspan="2">0.6</td><td>1.0</td><td rowspan="2">0.6</td><td>1.0</td></tr>
<tr><td>1.2</td><td>1.2</td><td>1.2</td><td rowspan="2">0.6</td></tr>
<tr><td>1.4</td><td>0.8</td><td>1.4</td><td>0.8</td><td>1.4</td></tr>
<tr><td>1.6</td><td>1.0</td><td>1.6</td><td>1.0</td><td>1.6</td><td>0.8</td></tr>
<tr><td>1.8</td><td>1.2</td><td>1.8</td><td>1.2</td><td>1.8</td><td rowspan="4">1.0</td></tr>
<tr><td>2.0</td><td rowspan="3">1.4</td><td>2.0</td><td rowspan="3">1.4</td><td>2.0</td></tr>
<tr><td>2.2</td><td>2.2</td><td>2.2</td></tr>
<tr><td>2.4</td><td>2.4</td><td>2.4</td></tr>
<tr><td>2.6</td><td>1.6</td><td>2.6</td><td>1.6</td><td>2.6</td><td rowspan="2">1.2</td></tr>
<tr><td>2.8</td><td>1.8</td><td>2.8</td><td>1.8</td><td>2.8</td></tr>
<tr><td>3.0</td><td>2.0</td><td>3.0</td><td>2.0</td><td>3.0</td><td>3.0</td></tr>
</table>

5.3.6 TVP Modelling Methodology

To determine the required number of turnstiles/access gates necessary to satisfy the passenger demand, a queuing LOS C density standard is adopted (TRB 1999c) with bandwidths as indicated in Table 5.4. Previous pedestrian modelling work undertaken by the author has shown that turnstile/access gate demand needs to be lower than turnstile/access gate capacity to achieve acceptable levels of queuing service (Hermant *et al.* 2010). In this work, a volume/capacity (*v*/*c*) versus queue space-density (*M*) relationship profile was plotted using microscopic modelling techniques (shown in Figure 5.6) in order to determine the required number of turnstiles/access gates necessary for a particular demand flow.

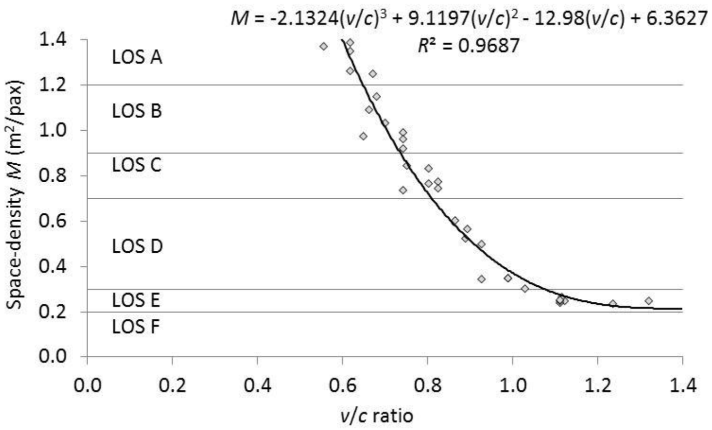


Figure 5.6: Space-queue density (*M*) versus *v*/*c* relationship

This is necessary, as according to De Neufville and Grillot (1982), the textbook formulas for calculating lengths of queues are generally not applicable for short durations of peaks at *v*/*c* levels approaching and exceeding unity. From this research, the author established that turnstile/access gate demand needs to satisfy a volume/capacity (*v*/*c*) ratio of between 0.74 and 0.80 to achieve a reasonable level-of-service of LOS C or better (Hermant *et al.* 2010).

From the relationship determined above, a cubic regression trendline is fitted that achieves a correlation coefficient R^2 of 0.9687 as indicated in Figure 5.6 above. Within the SP-model environment, the user is permitted to change the cubic coefficients only. The following cubic equation for modelling TVP requirements is used as a default in the SP-model:

$$M = -2.1324\left(\frac{v}{c}\right)^3 + 9.1197x\left(\frac{v}{c}\right)^2 - 12.980\left(\frac{v}{c}\right) + 6.3627$$

where *M* is the queuing space-density in m^2/pax.

It needs to be stressed that in this version of the SP-model, the coefficient values provided as default values for the TVP cubic regression are interim values as this aspect has not been researched in any depth. For example, the sensitivity of selecting different measurement area dimensions upstream of the turnstiles on the results of the relationship has not been investigated.

5.3.7 Evacuation Capacity and Speed

As already indicated, the SP-model tests for an evacuation scenario according to the NFPA 130 requirements. Accordingly, the following default evacuation capacities and walking speeds are proposed:

Table 5.7: Default evacuation capacity and speeds; (Source: NFPA 130 2003)

Infrastructure	**Exit Capacity**	**Travel Speed**
Platforms, corridors and ramps (ends) < 4% slope	89.4 pax/m/min	61.0 m/min
Stairs, stopped escalators and ramps > 4%: Ascending direction	62.6 pax/m/min	15.24 m/min*
Stairs, stopped escalators and ramps > 4%: Descending direction	71.7 pax/m/min	18.30 m/min*
Exit Lanes, doors and gates (min 914.4 mm wide):	89.4 pax/m/min	-

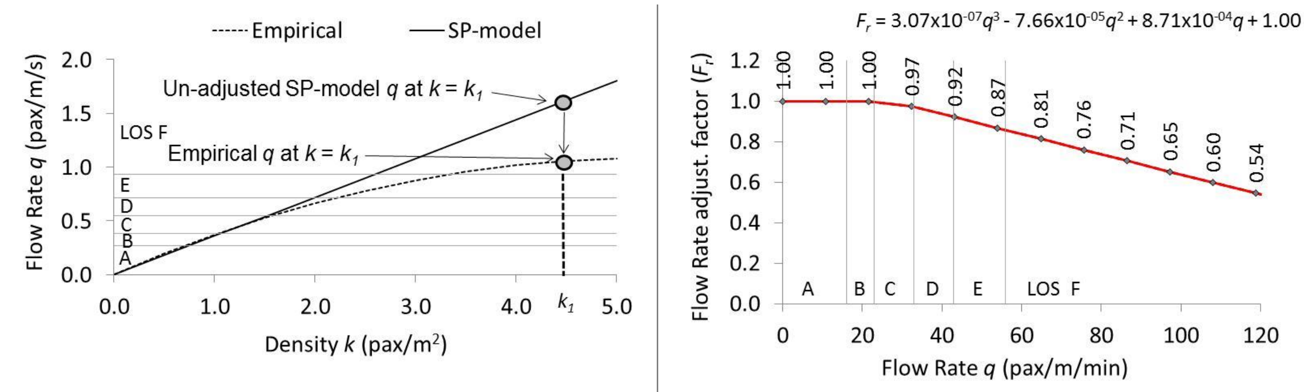
**Indicates vertical component of travel speed*

5.3.8 Flow Rate Adjustment Factor

One common method of model calibration is to modify parameters and model components until the simulations fit the fundamental flow-density diagram. The STV matrix modelling methodology employed by the SP-model (described in Subsection 5.2.6) intrinsically means that it ignores the effects of the fundamental macroscopic relationships i.e. it ignores the effects of increased person density on flow rates. The flow rate vs. density relationship is therefore a particularly important relationship to consider in the model to address this shortcoming.

At high pedestrian volumes, the STV matrix can (without adjustment) typically calculate flow rates exceeding realistic values. A Flow rate adjustment factor (F_r) is introduced in the model to factor values to within reasonable values in accordance with the empirical q vs. k relationship determined for the particular infrastructure type. Two Flow rate adjustment factors (F_r) are necessary and are represented by a cubic equation in the SP-model for both the staircase and skywalk (level surface) operations.

Figure 5.6 (*a.*) shows the upper limits of the empirical relationship between flow rate (q) and density (k) for staircases as a dotted line already discussed in Section 4.4. Here, as density increases, the rate of change of flow rate gradually decreases until a maximum flow rate is achieved at around a critical density (k_c) of 5.0 pax/m^2. The flow rate results of the SP-model are plotted as a straight line originating at the origin and follows the empirical curve until a density of around 1.5 pax/m^2 after which the empirical curve and SP-model line start deviating from each other. The F_r factor then essentially becomes the factor to reduce the SP-model value to the empirical curve value shown by the arrow in Figure 5.7 (*a.*).



(a.) Empirical vs. SP-model results

(b.) F_r factor for various values of q

Figure 5.7: Example of the staircase flow rate adjustment factor (F_r)

The Flow rate adjustment factor (F_r) is determined as follows:

$$F_r = \frac{Empirical\ q\ value}{SP - model\ q\ value}$$

Figure 5.7 (*b.*) shows the calculated flow rate adjustment factors (F_r) plotted as a function of varying flow rates (q). From the graph, lower flow rates have an F_r value of 1. Higher flow rates however require progressively greater adjustment values (i.e. with F_r values down to 0.6 for flow rate values exceeding 100 pax/m/min). The user is required to input the coefficients of the cubic trendline of the relationship plotted in Figure 5.6 (*b.*). In this version of the SP-model, default coefficients are provided which have been determined according to the empirical research conducted on staircases and skywalks (level surfaces) in this study.

The following cubic equations for modelling the flow rate adjustment factor (F_r) are proposed as defaults in the SP-model. Note that the user is permitted to change the cubic coefficients only.

<u>For staircases</u> : $F_r = 3.07\ x\ 10^{-7}.q^3 - 7.66\ x\ 10^{-5}.q^2 + 8.71\ x\ 10^{-4}.q + 1.00$

<u>For level surfaces</u> : $F_r = 2.08\ x\ 10^{-8}.q^3 - 1.12\ x\ 10^{-5}.q^2 - 1.42\ x\ 10^{-3}.q + 1.02$

5.4 Further Model Improvements

As this is the first version of the SP-model, it was not refined to exactly replicate the output of the microscopic results as this becomes progressively more difficult for small advancements. However, certain improvements can nevertheless be introduced with future versions of the model to improve the results as described below. Note that the impacts of these improvements on output accuracy is uncertain:

- The STV algorithms necessarily group people of similar walking speeds together who then continue to walk in these groups that pass through the various station infrastructure screenlines (as a group) at a specific time. This is not necessarily accurate; for example, an alighting volume of say 6 passengers (of similar walking group speed) would be given a total alighting time of 3 seconds using an alighting rate of 0.5 seconds per passenger. By definition, the STV algorithm therefore only introduces 6 passengers into the system after 3 seconds instead of 2 passengers every second. The accuracy of the SP-model could therefore be improved by distributing these walking group volumes over their respective alighting times (or on a second by second basis), but this would significantly complicate the spreadsheet.
- Allow for more than four platform-to-concourse staircases instead of the four per platform currently hardcoded in the model.
- Allow for differently sized platform-to-concourse stairs.
- Incorporate or introduce a delay time factor in the model to take into account the delay effects at circulation service elements such as at TVP batteries.
- As mentioned in Subsection 5.3.6, the function describing the volume/capacity (*v*/*c*) vs. space-density (*M*) relationship for turnstiles has not been researched in any depth and has been based on a preliminary simulation results only. This aspect should be researched further.
- Whilst the model calculates passenger boarding and alighting rates for each door facing the platforms, the distance matrix per coach (to the staircases) is based on a single (virtual) door located at the centre of the coach. Future model versions could incorporate multiple door distance matrices but the benefits in lieu of programming complications and more accurate results should be taken into consideration.
- Coach selection for boarding passengers is distributed across all coaches dependent on individual coach capacity. Future model versions could allow for a dynamically changing coach selection dependent on stair location on platforms and train departure time.
- The model automatically allocates coach passengers to the closest staircase i.e. the model does not have a stochastic route choice algorithm. In certain instances, a station may have a pair of stairs at the end of a platform. In this instance, the SP-model will allocate all passengers to one staircase providing very poor LOS results for that particular staircase. In order to overcome this problem, users should model only one staircase, but with the hypothetical width of the two staircases combined.
- The SP-model does not take into account platform ramps as infrastructure items, especially if in addition to staircases. If there are only ramps available on the platforms, then the user may use the stair inputs

to mimic ramp inputs, but must ensure that the correct ramp speed histogram is used in place of the stair data.

- The histogram mapping default input can be confusing to users and future versions of the model should seek to automate the histogram mapping function.
- The model assumes a user-defined distribution of passengers arriving from/walking to either side of the skywalk for all train passengers. An improvement in the program could provide individual skywalk distribution for passengers for each arriving train.
- The model currently does not allow for any transferring rail-to-rail passengers who although they use the platform staircases, do not use the full extent of the concourse or use the foyer or skywalks. Future versions of the SP-model could consider this.
- It is recommended that further research be conducted in South Africa which will further refine and develop the default parameters of the SP-model to be sensitive to input variations and environments.

6. FUNCTIONALITY ASSESSMENT OF THE SP-MODEL USING CASE STUDIES

The chapter begins by introducing the reader to the pedestrian level-of-service requirements used in railway station designs in this country as well as some of the assumptions and limitations inherent in the case study projects investigated. Both case study stations, assessed with both the SP-model and VISSIM models, are then presented, with input criteria and model output results and conclusions discussed separately for each station. The results of the SP-model, as evaluated against macroscopic calculation methods are then presented per station followed by a concluding discussion on the overall applicability of the SP-model in industry.

The assessment process incorporates the quantitative comparison of the SP-model results to the VISSIM microscopic modelling results to ascertain the potential use of the SP-model as a first-order station design tool. The author has been directly involved with the pedestrian microscopic modelling of several railway stations in South Africa including the Khayelitsha and Nyanga stations (Goba 2009a), Windermere Station (Goba 2009b), Langa Station (Goba 2009c), Cape Town Station (Goba 2009d), Moses Mabhida Station (Goba 2009e) and Bridge City Station (Goba 2010). All these stations were originally modelled using the VISSIM microscopic simulation software package. For the purposes of validating the SP-model, two case study projects were selected viz. the new Century City Station (previously known as the Windermere Station) and the upgraded Langa Station located in Cape Town, South Africa.

The spatial assessments are conducted by comparing the SP-model results against the results of the state-of-the-art VISSIM microscopic simulation software where pedestrians are modelled as individual agents. Spatial output results of the stairs, concourse, foyer and skywalks were used for comparison purposes as the VISSIM model version (v5.10) used at the time of the assessment was restricted to these infrastructure elements. As indicated in Section 1.6, the VISSIM software package was calibrated with the same empirical data collected in this research, in order to discount the effects of the built-in default European attributes.

Note that whilst the calibration of the SP-model incorporated the results of the empirical data collected, the functional assessment of the model incorporated the evaluation of the SP-model results against the results of microscopic modelling conducted through two case study applications. The comparison of the SP-model against real-time observations would have offered a better validation process, but this was not possible due to the significant resource requirements to undertake such surveys.

6.1 Introduction

The two case study stations afforded a practical way to demonstrate and present an overview of the graphic outputs provided by the model as well as a means to validate the model. The case studies also provided an additional opportunity to present to the user the various interpretations of the spatial input parameters that varied slightly from the generic input sketch. On the basis of the output graphs, conclusions are drawn regarding the operational assessments of the various infrastructure elements within the case study stations.

As the case studies discussed in this chapter are the first extensive (academic) application of the SP-model, recommendations are given in the User Manual (included in Appendix L) for the handling of the tool with respect to the various worksheets of the model.

In recent years, safety and security are increasingly being emphasised in the railway industry (SANS 2005). Towards addressing this, the SP-model had to meet specific requirements concerning passenger safety in terms of the ability to test the station evacuation scenario. This was considered particularly important since evacuation requirements may become the critical criteria when sizing station infrastructure. Specific requirements for addressing emergency evacuation events as contained in the National Fire Protection Association (NFPA) standard for fixed guideway transit and passenger rail stations (NFPA 130 2003) have been incorporated in the model and are briefly reviewed in the case studies.

6.2 Station Infrastructure Evaluation

As per the South African NGS design guidelines (SARCC 1997), station infrastructure sizing requirements have been based on the following minimum acceptable levels-of-service (LOS) for each of the infrastructure elements:

Stairs: LOS D
All other station elements: LOS C

Note that the published NGS standard proposes a LOS B design criteria for walkways; refer to Table 2.1 in Subsection 2.1.2, which was subsequently unofficially reviewed to a LOS C standard by PRASA during the design process undertaken in 2008/9.

From the literature review, evaluation criteria (incorporating either densities or flow rates) calculated to be worse than the acceptable level-of-service are considered only a concern if they last longer than 30 seconds. The argument is that passengers become impatient and more reckless when they are delayed for more than this time period according to Hoogendoorn *et al.* (2007).

The assessment methodology employed using microscopic modelling for station design is as follows: If the pedestrian modelling output conducted over the assessment period (with density and/or flow rate parameters output in ten second intervals) reveals an unacceptable LOS (i.e. lasting for longer than 30 seconds or three intervals) then the passenger loading imposed on the station would be considered to exceed acceptable operational levels. Accordingly, the spatial provision of the tested pedestrian infrastructure would need to be increased such that the LOS criteria limit would not be violated for a period of longer than 30 seconds.

In addition to designing for the peak loads during normal operations, the station evacuation time plays an important role in evaluating the emergency infrastructure requirements. In this instance, there can be little argument against designing for the maximum possible evacuation load. In line with international standards, pedestrians within a station facility should be able to evacuate the platform within four minutes and the station building within six minutes respectively from the time the fire alarm is activated (NFPA 130 2003).

6.2.1 Pedestrian Level-of-Service Criteria

In terms of assessing the pedestrian spatial parameters of the case study station designs, the peak 30-minute period was modelled according to a projected future horizon year train schedule with predicted alighting and boarding volumes identified for the particular scenario.

If the pedestrian modelling density and/or flow parameter output conducted over this peak period revealed an unacceptable LOS, then additional infrastructure or widening of infrastructure is proposed in order that the longitudinal LOS criteria complies to within the specification or within acceptable time limits. For the purposes of this study, the author adopted the TCQSM level-of-service classification system (TRB 1999c) which has been adapted from Fruin (1971) for public transport terminals and allows for a greater degree of pedestrian crowdedness that public transport users can be expected to experience at such facilities.

The question of what LOS transgression time limit is acceptable for design purposes falls to the discretion of the planners and depends on attitudes towards safety and efficiency, as well as location and time of day. In some instances, there may even be cultural issues to consider with regard to attitudes to personal space and level of congestion that can be tolerated, but these aspects are beyond the scope of this study.

6.2.2 Assumptions and Limitations

To simplify the microscopic modelling process, the following assumptions were made:

- 11 x 5M train sets were used in the Century City station modelling simulations and 12 x 8M train sets were used in the Langa station modelling simulations.

- For the Century City station modelling, a turnstile capacity of 30 passengers per minute (pax/min) was assumed to be operational in the 2015 horizon year. The implementation of the higher 50 pax/min capacity access “flap” gates was also tested in Scenario 2 for this station.

- For the Langa Station modelling, a turnstile capacity of 45 passengers per minute (pax/min) was assumed to be operational in 2025 to best represent the higher capacity access “flap” gates.

- The impact of ticket sales on station operation and ablution facility use was excluded from all modelling scenarios.

6.2.3 ARIMA Time-Series Statistical Evaluation Technique

The next two sections present the results of the application of the SP-model to the two station case studies. Here the longitudinal (time-series) results of the SP-model are compared to the results of the VISSIM microscopic model both graphically (viz. by observation) and statistically. Before presenting the results, it is necessary to first provide a brief introduction of the time series statistical technique used to compare the two output streams.

A time series dataset consists of a longitudinal series of observations or results, like density or flow rates, at successive points in time, usually at equally spaced intervals. The one purpose of a time series analysis is to describe the time series by a mathematical model, which provides an appropriate description of the systematic and random variation in a dataset. The time-series analysis method used in this study uses a sophisticated ARIMA[2] modelling technique. ARIMA is the anagram for "*Autoregressive Integrated Moving Average*", after the three components, auto regression[3] (AR), integration and moving averages (MA) of the general ARIMA model (SPSS 1994).

In the ARIMA modelling approach, the behaviour of a time series is described in terms of the way in which observations at different times are related statistically with each other. It consists of methods, which fit autoregressive and/or moving-average models to the dataset after accounting for seasonal adjustments (Box and Jenkins 1976; McCleary and Hay 1980; Armitage and Berry 1987; Chatfield 1996).

ARIMA modelling is usually conducted in three stages. Firstly, a reasonable model based on patterns of autocorrelation is identified. Secondly, the parameters of the tentative model are estimated so that their values are statistically significant and consistent with assumptions of stationary. Thirdly, the adequacy of the model with its estimated parameter values is evaluated. This iterative identification/estimation/diagnosis procedure continues until an adequate and most parsimonious ARIMA model has been achieved for a given time series. (Box and Jenkins 1976; McCleary and Hay 1980; Armitage and Berry 1987; Martinez-Schnell and Zaidi 1989; Tennenbaum and Fink 1994; Chatfield 1996).

For the purposes of this research, the time series data tested consisted of the time series difference between the results of SP-model and the microscopic model. Theoretically, if the SP-model replicates the microscopic model exactly, the longitudinal plot of the differences will be zero for all time points. The ARIMA model therefore seeks to test this as the null hypothesis. A more detailed explanation of the ARIMA statistical process used in this study can be found in Appendix K.

6.3 Case Study 1: Century City Railway Station

6.3.1 Locality and Facility Purpose

The station is a new station, proposed on the Monte Vista line between Cape Town and Bellville Stations. Figure 6.1 shows the concourse layout and areas and points of spatial assessment used for both the microscopic model and the SP-model. The figure also indicates the dimensions of the infrastructure items assessed.

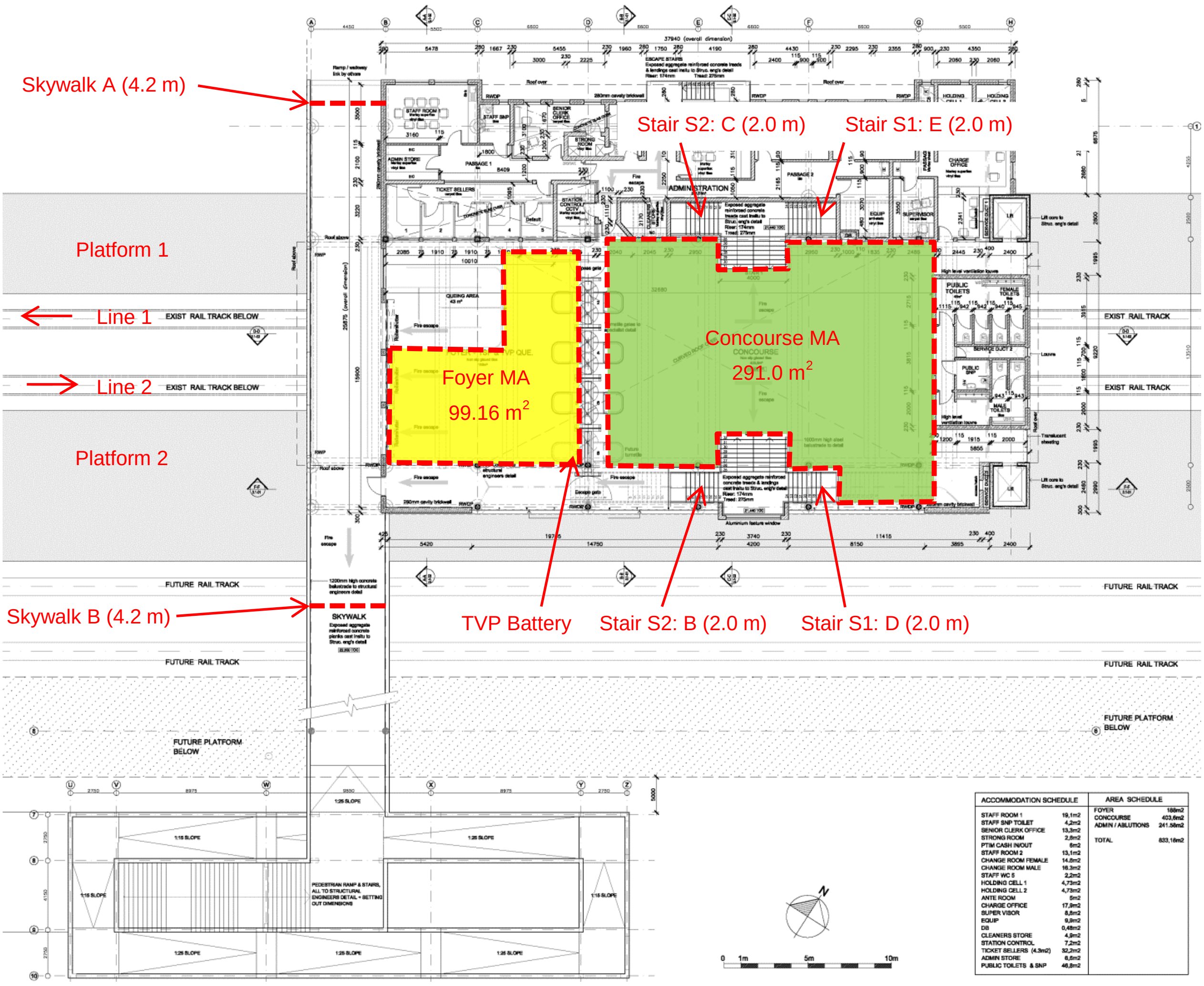
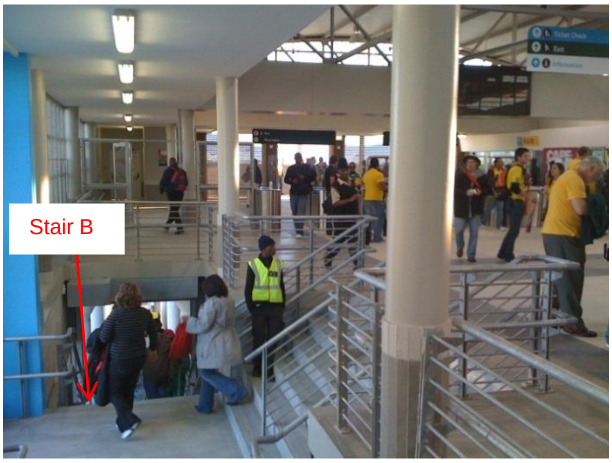


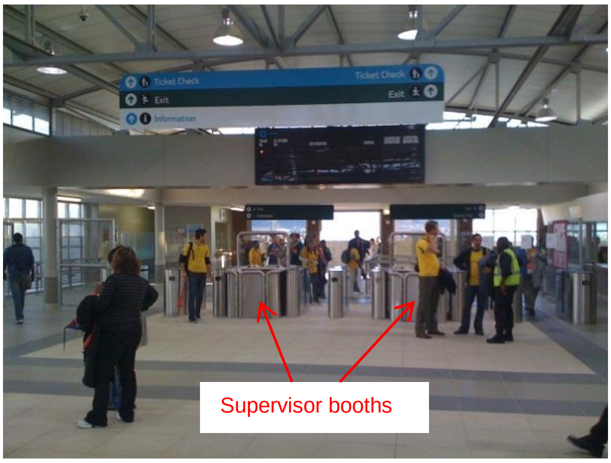
Figure 6.1: Concourse layout of Century City station; (Source: blueprint Architects)

The figure shows two functional rail lines (viz. lines 1 and 2) served by two side platforms, with the possibility of additional lines and a platform to the south of the existing lines.

To give an indication of the layout of the recently completed station facility, various photographs depicting the concourse layout is shown in Figure 6.2. Note that whilst high speed access gates were installed, these are not ticket controlled and manual ticket checking still needs to take place, which is the reason for the installation of supervisor booths located within the TVP battery.



View of the concourse-to-platform staircases (stair B)



View of the TVP battery from the concourse area

View of the overhead concourse from the Cape Town side

View of the side platform emergency exit gate

Figure 6.2: Photographs depicting the newly built Century City Station (taken in July 2010)

6.3.2 Passenger Volumes

Table 6.1 shows the AM peak 15-minute design train passenger demand used in the pedestrian modelling analysis. The alighting volume is based on 205 passengers over each of the three trains and the boarding volume is based on 129 passengers over each of the three trains. Passenger volumes have been adjusted upwards in the first train to account for peaking effects.

Table 6.1: Scenario 1 – AM peak 15-min train schedule and passenger volumes in 2015; (Goba 2009b)

Clock Time (sec)	Direction	Platform	Boarding (pax)	Alighting (pax)	Total (pax)
660	To Cape Town	1	**195**	**305**	500
1080	From Cape Town	2	**129**	**205**	334
1200	To Cape Town	1	**73**	**118**	191
		Total	397	628	1,025
Street-to-street Volume : not considered					

Passenger volumes for Scenario 2 are shown in Table 6.2 which has been modelled using high speed access flap gates at 50 pax/min capacity instead of turnstiles for the year 2025. A 14% passenger volume growth from 2015 to 2025 is assumed. This scenario also includes the skywalk street-to-street volumes

Table 6.2: Scenario 2 – Simultaneous Train Arrivals in 2025; (Goba 2009b)

Clock Time (sec)	Direction	Platform	Boarding (pax from South side)	Alighting (pax to North side)	Total (pax)
1080	To Cape Town	2	**148**	**235**	382
1080	From Cape Town	1	**148**	**235**	382
		Total	296	470	764
Street-to-street Volume : 18 pax/min					

Note that for both scenarios, 75% of boarding passengers arrive from the Kensington side and 25% from the Century City side. After alighting, all passengers proceed to the Century City side.

6.3.3 Spatial Assessment Comparisons

The output plots presented in this subsection show both the results of the SP-model (red line) and the VISSIM model (black line) on the same longitudinal time scale axis. Vertical dotted lines in the output plots indicate scheduled train arrival times. Note that the VISSIM microscopic model cannot gather density data on stairs, and so only flow rate data at the mid-point landing of the staircases has been used for comparative purposes. Since the microscopic modelling calculates data outputs for every 10 second interval, there are more plotted data points than the SP-model outputs, which is based on 60 second interval outputs. Note that spatial assessments were not conducted for the platform areas since the results for such infrastructure is largely dependent on the platform measurement area selected and the location on the platform itself.

<u>SCENARIO 1</u>

Scenario 1 longitudinal outputs for Century City Station are indicated in Figures 6.3 and 6.4 incorporating plates A1 to A4 and plates B1 to B4 respectively. Note, for printing clarity purposes, the results are reproduced without the LOS colour bandwidths, a standard feature provided in the SP-model.

Staircases:

Plates A1 and A2 show the comparative longitudinal flow rate plots of staircases S1 and S2 on Platform 1 respectively. From Plate A1, the 60-second interval SP-model output appears to closely approximate the 10 second interval results of the micromodel. For staircase S1, the micromodel revealed a 30-second duration within each of the LOS D and E bandwidths whilst the SP-model predicts a full 60 seconds within the LOS D bandwidth. This is attributable to the fact that the SP-model uses one-minute assessment intervals and can therefore not produce output results shorter than this time interval.

From visual observation, the results shown in Plate A2 reveal that the SP-model closely matches the microscopic model results. Both models predict a worst case LOS D scenario albeit for different time durations viz. 10 seconds for the micromodel and 60 seconds for the SP-model. This is again attributable to the minimum 60-second interval assessment period of the SP-model.

The results shown in Plates A3 and A4 show the comparative longitudinal flow rate plots of staircases S1 and S2 on Platform 2 respectively. From Plate A3, it can be observed that there is a good quantitative match with both models yielding a worse LOS C. The SP-model however allocates a 60-second duration in LOS C versus only 30 seconds duration for the micromodel. Plate A4, showing the results for the S2 staircase shows an exact match for both model results in terms of duration within the various LOS bandwidths.

Skywalks:

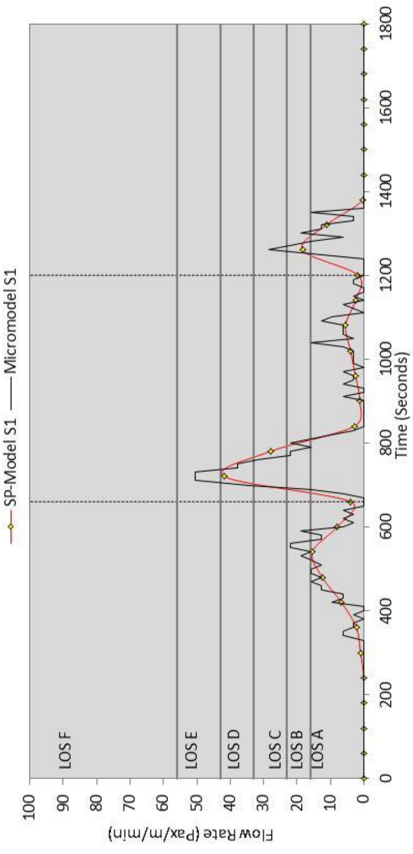
Figure 6.4 shows the Plate B results and includes the longitudinal plots of the skywalk flow rates as well as the longitudinal density plots for the concourse and foyer areas. Plates B1 and B2 show the comparative plots for the skywalk output plots for sides A and B respectively. From the results shown in Plate B1, both models predict a minimum time duration within the LOS C bandwidth (i.e. the worst LOS case scenario) according to their interval assessment period viz. 10 seconds for the mircomodel and 60 seconds for the SP-model. From Plate B2 showing the results of the Kensington side skywalk, both models predict flow rates within the LOS A bandwidth.

Foyer:

The results in Plate B3 shows the longitudinal foyer density plots and here the SP-model predicts a marginally worse LOS threshold (viz. LOS C) than the micromodel which only predicted a worse case LOS B. Cognisance of the narrow LOS B density bandwidth must however be taken into account when evaluating this LOS result difference. Note that the SP-model density plots are represented by a 60-second moving average[38] instead of a density plot per second to overcome the problem of zero STV matrix entries. The lower density (better LOS) values shown by the micromodel may be indicative of delay experience at the turnstile battery upstream of the foyer. Turnstile delay is not considered in this first version of the SP-model. The delay effect of the turnstiles creates a longer walking time and a flattening of the output peaks.

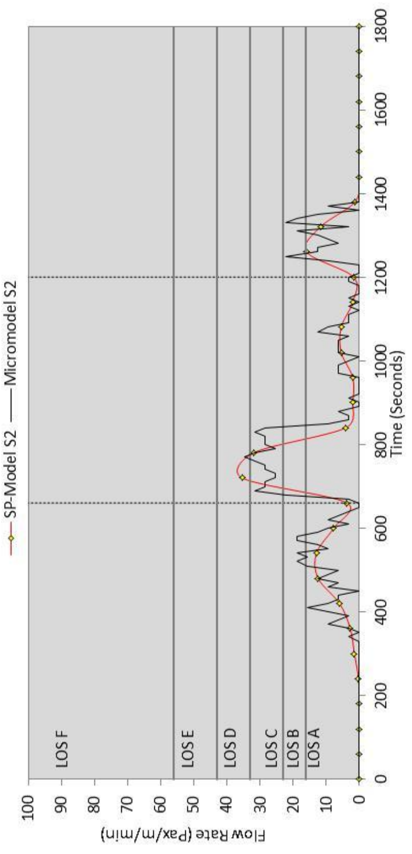
Concourse:

Plate B4 shows the results of the concourse density plot with the SP-model predicting a worse case LOS B density after the train arrival at time t = 660 sec. By visual comparison, the concourse plot follows the same peaking pattern exhibited by the micromodel longitudinal plot, except with a higher peaking amplitude. As in the case of the Foyer results, the lower amplitude of the micromodel (when compared to the SP-model) is attributable to the delay effects of the turnstiles which has not been considered in this version of the SP-model.



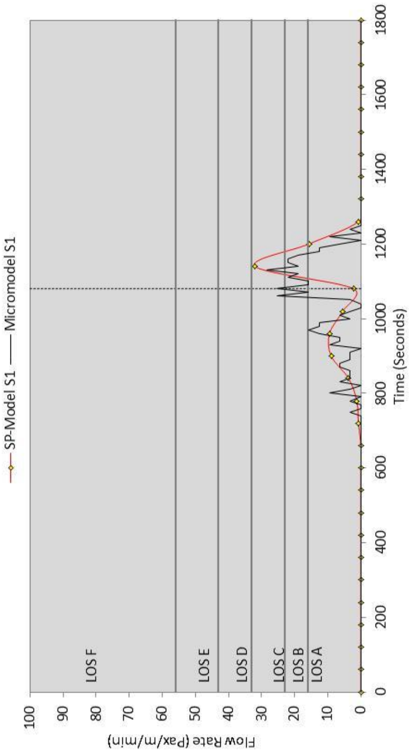
		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1620	60	60	60	0	0
	Total Time (%)	90.0%	3.3%	3.3%	3.3%	0.0%	0.0%
Micro Model	Total Time (sec)	1630	90	20	30	30	0
	Total Time (%)	90.6%	5.0%	1.1%	1.7%	1.7%	0.0%

A1: Platform 1, Staircase S1 (E)



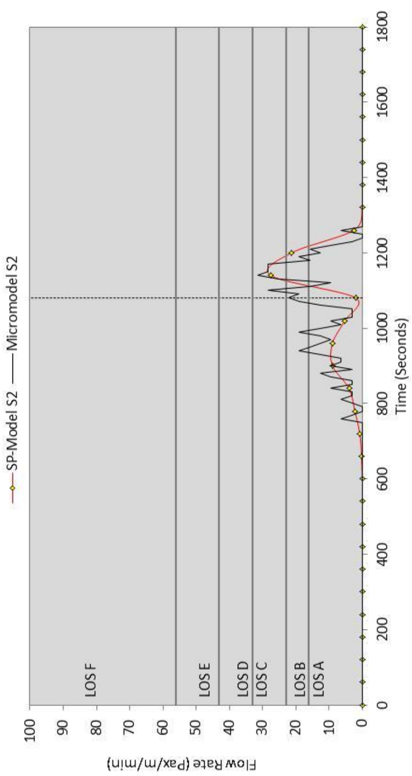
		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1680	0	60	60	0	0
	Total Time (%)	93.3%	0.0%	3.3%	3.3%	0.0%	0.0%
Micro Model	Total Time (sec)	1550	90	150	10	0	0
	Total Time (%)	86.1%	5.0%	8.3%	0.6%	0.0%	0.0%

A2: Platform 1, Staircase S2 (C)



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1740	0	60	0	0	0
	Total Time (%)	96.7%	0.0%	3.3%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1710	60	30	0	0	0
	Total Time (%)	95.0%	3.3%	1.7%	0.0%	0.0%	0.0%

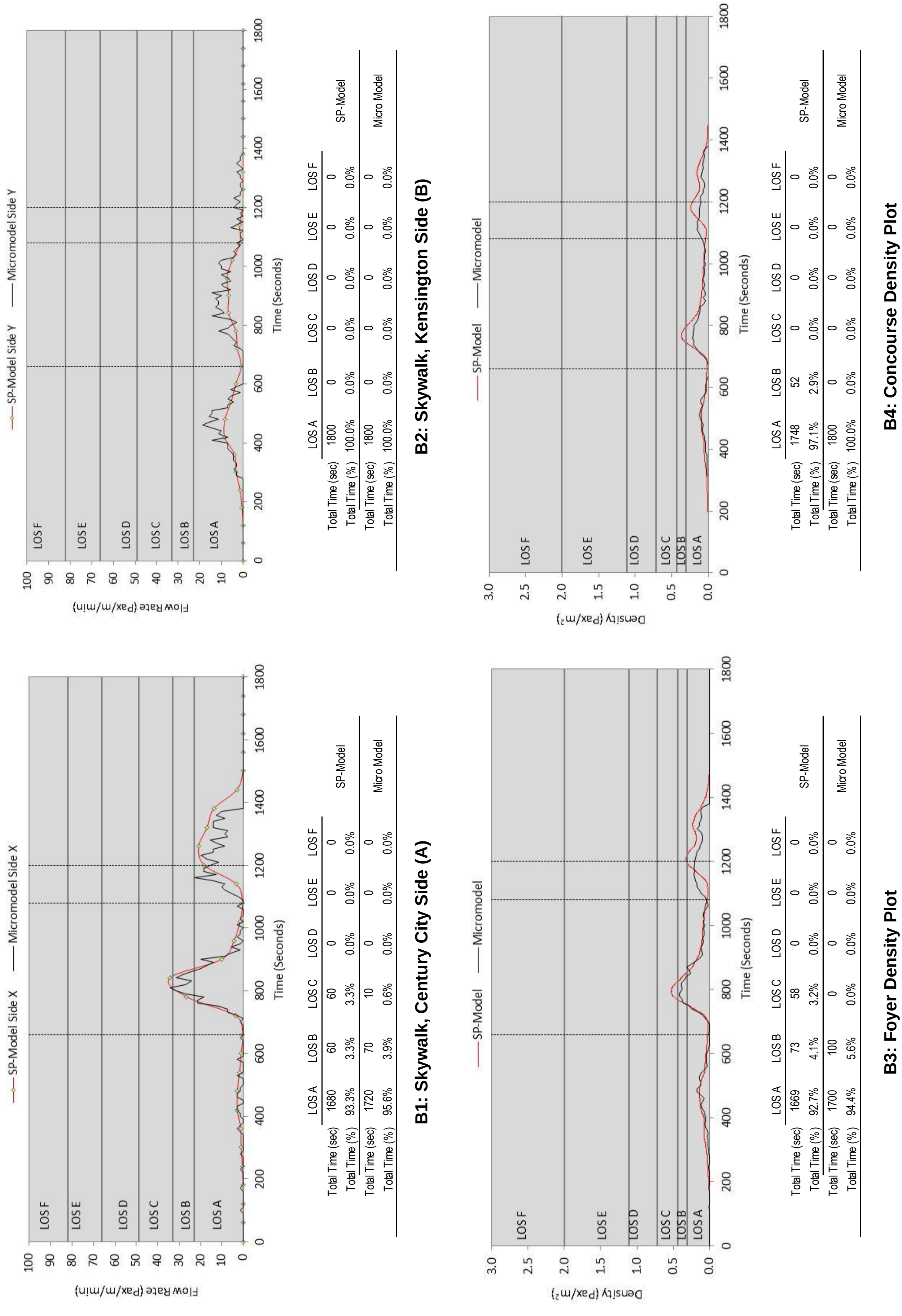
A3: Platform 2, Staircase S1 (D)



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1680	60	60	0	0	0
	Total Time (%)	93.3%	3.3%	3.3%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1680	60	60	0	0	0
	Total Time (%)	93.3%	3.3%	3.3%	0.0%	0.0%	0.0%

A4: Platform 2, Staircase S2 (B)

Figure 6.3: Century City Station longitudinal flow rate plots: Scenario 1, Plate A



B1: Skywalk, Century City Side (A)

		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1680	60	60	0	0	0
	Total Time (%)	93.3%	3.3%	3.3%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1720	70	10	0	0	0
	Total Time (%)	95.6%	3.9%	0.6%	0.0%	0.0%	0.0%

B2: Skywalk, Kensington Side (B)

		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

B3: Foyer Density Plot

		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1669	73	58	0	0	0
	Total Time (%)	92.7%	4.1%	3.2%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1700	100	0	0	0	0
	Total Time (%)	94.4%	5.6%	0.0%	0.0%	0.0%	0.0%

B4: Concourse Density Plot

		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1748	52	0	0	0	0
	Total Time (%)	97.1%	2.9%	0.0%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Figure 6.4: Century City Station longitudinal flow rate/density plots: Scenario 1, Plate B

SCENARIO 2

The longitudinal outputs for Scenario 2 for Century City Station are shown in Figures 6.5 and 6.6 incorporating plates C1 to C4 and plates D1 to D2 respectively

Staircases:

Plates C1 and C2 show the results of the comparative longitudinal flow rate plots of staircases S1 and S2 on Platforms 1 and 2 respectively. Since train arrival times are simultaneous for this scenario arriving at *t* = 1080 sec, both sets of staircases for each platform will experience the same loading pattern due to the identical alighting and boarding volumes.

For the results of staircase S1 shown in Plate C1, both models predict a worst case LOS D scenario, with the SP-model predicting a minimum 60 second duration in this LOS bandwidth when compared to only 20 seconds predicted by the micromodel. By visual observation, the graphic output of the SP-model closely matches the micromodel results and shows peaking immediately after train arrival as expected.

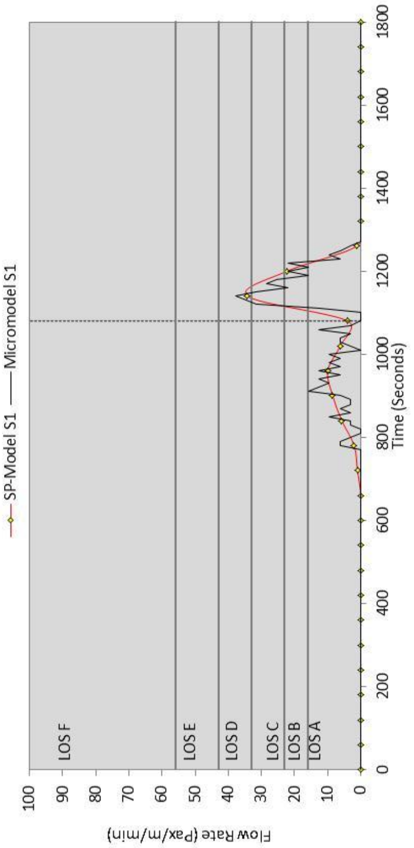
Plate C2 shows the results of longitudinal flow rate plots for the staircases on both platforms closest to the foyer. Both models predict a worse case LOS C result with the SP-model predicting a minimum 60 second duration in this bandwidth compared to a 100 second duration predicted by the micromodel in this bandwidth.

From visual inspection of the graph outputs, the micromodel plot has a flatter peak after train arrival than predicted by the SP-model. It is suggested that this is due to pedestrians maintaining their inter-personal distances. As already discussed in Subsection 4.4.1, this "*self-regulating*"[46] phenomenon was also observed by Brocklehurst (2005c) at racecourse venues, where he observed that despite crowded conditions, people tried to maintain their preferred inter-personal distance between each other.

Plates C3 and C4 show the results of the longitudinal flow rate plots for the skywalk for the Century City side (Side A) and Kensington side (Side B) respectively. The results shown in Plate C3 indicate that both models predict a LOS C worst case scenario with the SP-model predicting a 120 second duration in this bandwidth compared to a 140 second duration predicted by the micromodel. The remainder of the SP-model output appears to closely match the micromodel results. Note that, for this scenario, street-to-street pedestrians were incorporated in the simulation showing a constant 4 pax/m/min reading for the graphs. Note that the micromodel results were terminated at *t* = 1370 seconds and this is the reason for zero values past this point for this output. Also note that from *t* = 1200 to 1300 seconds, the micromodel results tend to be more spread than the SP-model due to the "*self-regulating*" effect already described.

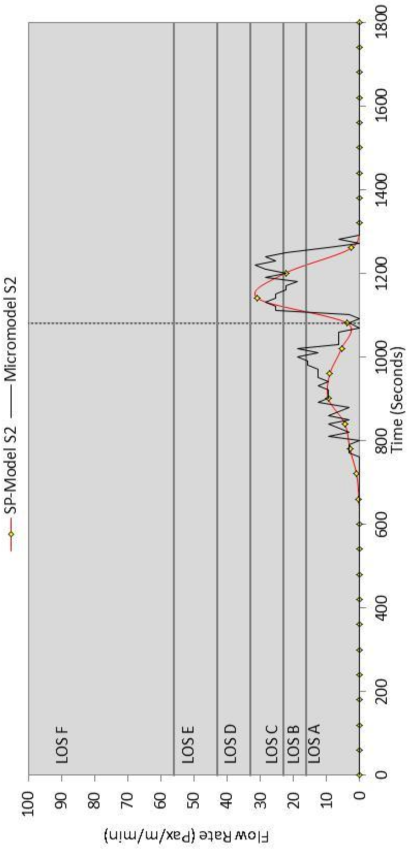
Skywalks:

Plate C4 shows the longitudinal results for the Kensington Side skywalk. Here, the micromodel predicts a slight peak into the LOS B bandwidth for a 20-second period, a period too small to be identified by the SP-model. The SP-model therefore predicts a LOS A operation for the entire analysis period but nevertheless provides a good approximation when compared to the micromodel results. As per the simulation results shown in Plate C3, the micromodel assessment was terminated at *t* = 1370 seconds and is the reason for the zero values past this point for the micromodel results.



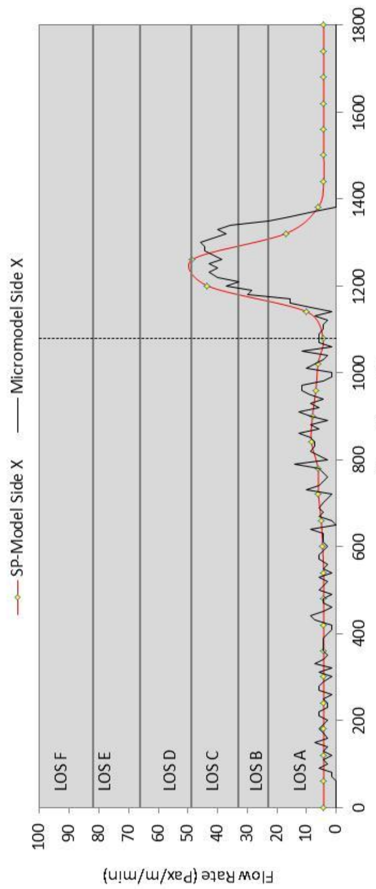
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F	
Total Time (sec)	1680	60	0	60	0	0	SP-Model
Total Time (%)	93.3%	3.3%	0.0%	3.3%	0.0%	0.0%	
Total Time (sec)	1710	30	40	20	0	0	Micro Model
Total Time (%)	95.0%	1.7%	2.2%	1.1%	0.0%	0.0%	

C1: Platform 1 and 2, Staircase S1 (E & D)



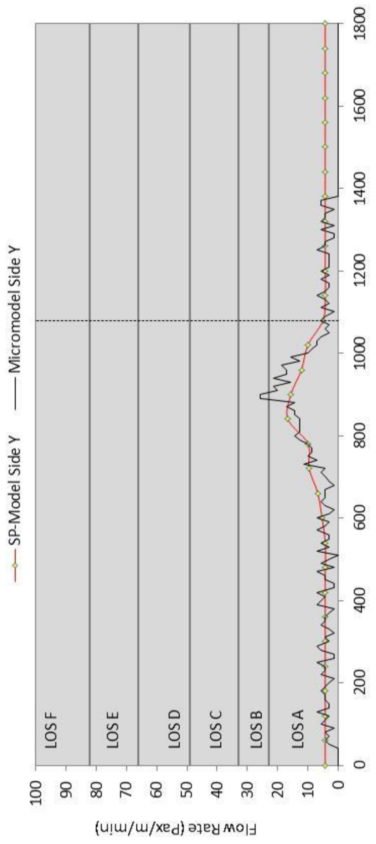
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F	
Total Time (sec)	1680	60	60	0	0	0	SP-Model
Total Time (%)	93.3%	3.3%	3.3%	0.0%	0.0%	0.0%	
Total Time (sec)	1630	70	100	0	0	0	Micro Model
Total Time (%)	90.6%	3.9%	5.6%	0.0%	0.0%	0.0%	

C2: Platform 1 and 2, Staircase S2 (C & B)



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F	
Total Time (sec)	1680	0	120	0	0	0	SP-Model
Total Time (%)	93.3%	0.0%	6.7%	0.0%	0.0%	0.0%	
Total Time (sec)	1630	30	140	0	0	0	Micro Model
Total Time (%)	90.6%	1.7%	7.8%	0.0%	0.0%	0.0%	

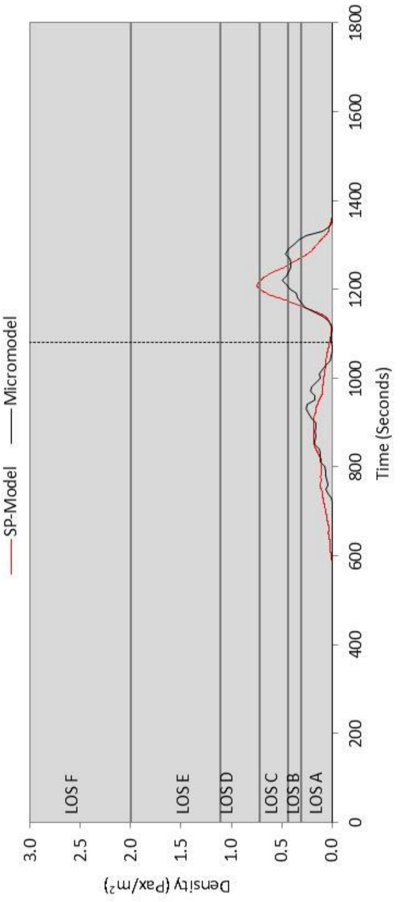
C3: Skywalk, Century City Side (A)



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F	
Total Time (sec)	1800	0	0	0	0	0	SP-Model
Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
Total Time (sec)	1780	20	0	0	0	0	Micro Model
Total Time (%)	98.9%	1.1%	0.0%	0.0%	0.0%	0.0%	

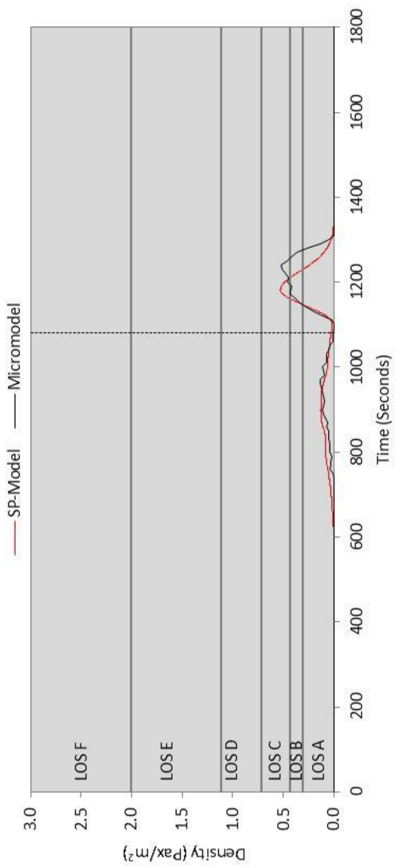
C4: Skywalk, Kensington Side (B)

Figure 6.5: Century City Station longitudinal flow rate plots: Scenario 2, Plate C



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1690	27	64	19	0	0
	Total Time (%)	93.9%	1.5%	3.6%	1.1%	0.0%	0.0%
Micro Model	Total Time (sec)	1650	110	40	0	0	0
	Total Time (%)	91.7%	6.1%	2.2%	0.0%	0.0%	0.0%

D1: Foyer Density Plot



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1716	36	48	0	0	0
	Total Time (%)	95.3%	2.0%	2.7%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1670	70	60	0	0	0
	Total Time (%)	92.8%	3.9%	3.3%	0.0%	0.0%	0.0%

D2: Concourse Density Plot

Figure 6.6: Century City Station longitudinal density plots: Scenario 2, Plate D

Foyer:

Plate D1 shows the results of the longitudinal foyer density plot. For this plot, the SP-model predicts a worst case LOS D operation for a 19-second duration compared to the worst-case LOS C predicted by the micromodel for a duration of 40 seconds. The micromodel result plot again shows a flatter curve after train arrival levelling out at the LOS B/C density limit. In this instance, it is suggested that the peak flattening is due to the delaying impact of the turnstiles on pedestrian movement rather than the "*self-regulating*" phenomena.

Concourse:

Plate D2 shows the results of the longitudinal concourse density plot. Here, both models predict a worse case LOS C operation with the SP-model predicting a 48-second duration and the micromodel predicting a 60-second duration in this LOS bandwidth. As per the observations above for the foyer plot, the micromodel has a slightly flatter peak (and peak spread) due to the delaying effects of the turnstiles.

6.3.4 Statistical ARIMA Assessment

The results of the ARIMA time-series model evaluation used to test the statistical correlation of the two models is provided in Table 6.3 below. The statistical testing has been conducted using the STATISTICA commercial computer package and was exclusively undertaken by the Centre for Statistical Consultation at the University of Stellenbosch during March 2011.

Table 6.3: ARIMA statistical results for Century City station

	Plate	Setting*	Model	*P*-Statistic				Conclusion
				Constant (*c*)	*p*(1)	*p*(2)	*p*(*n*)	
Scenario 1	A1	c1p1s1	MA(2)	0.053	0.000	0.000		Models correlate
	A2	c1p1s2	AR(2)	0.526	0.944	0.003		Models correlate
	A3	c1p2s1	AR(2)	0.387	0.019	0.007		Models correlate
	A4	c1p2s2	AR(2)	0.281	0.769	0.206		Cannot use ARIMA
	B1	c1sx	ARMA(1,1)	0.183	0.403	0.009		Models correlate
	B2	c1sy	AR(3)	0.158	0.097	0.224	0.023 at *n* =3	Models correlate
	B3	c1f	MA(1)	0.133	0.030	-		Models correlate
	B4	c1c	MA(1)	0.074	0.101	-		Cannot use ARIMA
Scenario 2	C1	c2p1&2s1	AR(2)	0.435	0.554	0.038		Models correlate
	C2	c2p1&2s2	AR(2)	0.215	0.683	0.000		Models correlate
	C3	c2sx	ARMA(1,1)	0.971	0.867	0.000		Models correlate
	C4	c2sy	AR(1)	0.708	0.022	-		Models correlate
	D1	c2f	MA(4)	Data cannot be calculated				Cannot use ARIMA
	D2	c2c	ARMA(1,1)	0.722	0.627	0.827		Cannot use ARIMA

** Settings Legend:*

c1 or c2: Century City station scenarios 1 or 2

p1 or p2: platforms 1 or 2

s1 or s2: staircases 1 or 2

f: foyer

c: concourse

sx or sy: skywalk side x or y

Table 6.3 shows the various types of ARIMA models that were applied for the comparison testing. All scenario tests, except “c1p2s2” (Plate A4) and “c1c” (Plate B4) in Scenario 1 and “c2f” (Plate D1) and “c2c” (Plate D2) in Scenario 2 could be assigned an ARIMA model. For either of the MA, AR or ARMA models to apply, the *P*-statistic of the lag coefficients *q*(1), *q*(2),…*q*(n) need to be less than the 5% level of significance. Only lag coefficients up until the 5th coefficient level were tested due the limited data points in the model viz. 30 one-minute data points. An appropriate ARIMA model is determined according to which of the the five lag coefficients have a *P*-statistic less than the 5% level of significance. An ARIMA model cannot be applied to more than five lag coefficients due to insufficient points in the data.

Once a suitable model is applied, then the *P*-statistic of the constant term is checked if greater than the 5% level of significance (tested against a Null hypothesis that defines the constant term to equal zero). A constant term with a *P*-statistic greater than 5% therefore indicates that there is correlation between the two models.

6.3.5 Conclusions

Table 6.4 summarises the results of the worst LOS outputs obtained during the modelling analysis for both models. The results shown in bold italics indicate where ARIMA testing could not be undertaken and where a correlation between the two models could therefore not be verified.

Table 6.4: Comparison of worst-case model results for Century City station

Infrastructure	Item	Platform	Scenario 1		Scenario 2	
Model			**VISSIM**	**SP-Model**	**VISSIM**	**SP-Model**
Period			**AM**		**AM**	
Assessment year			2015		2025	
Street-to-street included ?			No	No	Yes	Yes
Staircases	S1 (E)	1	E (30 sec)	D (60 sec)	D (20 sec)	D (60 sec)
	S1 (D)	2	C (30 sec)	D (60 sec)		
	S2 (C)	1	D (10 sec)	D (60 sec)	C (100 sec)	C (60 sec)
	S2 (B)	2	***C (60 sec)***	***C (60 sec)***		
Skywalk	A	n/a	C (10 sec)	C (60 sec)	C (140 sec)	C (120 sec)
	B	n/a	A (1800 sec)	A (1800 sec)	B (20 sec)	A (1800 sec)
Foyer	n/a	n/a	B (100 sec)	C (58 sec)	***C (40 sec)***	***D (19 sec)***
Concourse	n/a	n/a	***A (1800 sec)***	***B (52 sec)***	***C (60 sec)***	***C (48 sec)***

The platform-to-concourse staircases were found by both models to operate at acceptable levels-of-service for the predicted 2015 passenger volumes (i.e. LOS D or better) but have little spare capacity, especially for Scenario 1, staircase S1 where the micromodel calculated a brief 30-second duration in the LOS E bandwidth.

In light of the findings of this case study investigation, the proposed spatial arrangements for the new Century City station that were determined by micromodelling results were found to be adequate for the predicted 2015 and 2025 pedestrian volumes and are adequately represented by the results of the SP-model. The SP-model does however give marginally pessimistic LOS density values for the foyer and concourse infrastructure items, but this can be attributable to the effect of ignoring turnstile delay in this version of the model. This difference is however negligible and can be considered acceptable in view of the primary objective of the SP-model as a first-order spatial assessment tool.

6.4 Case Study 2: Langa Railway Station

6.4.1 Facility Purpose

Figure 6.7 shows the concourse layout and dimensions of the various infrastructure assessment areas. Figure 6.8 shows a snapshot of the 3D VISSIM animation model output.

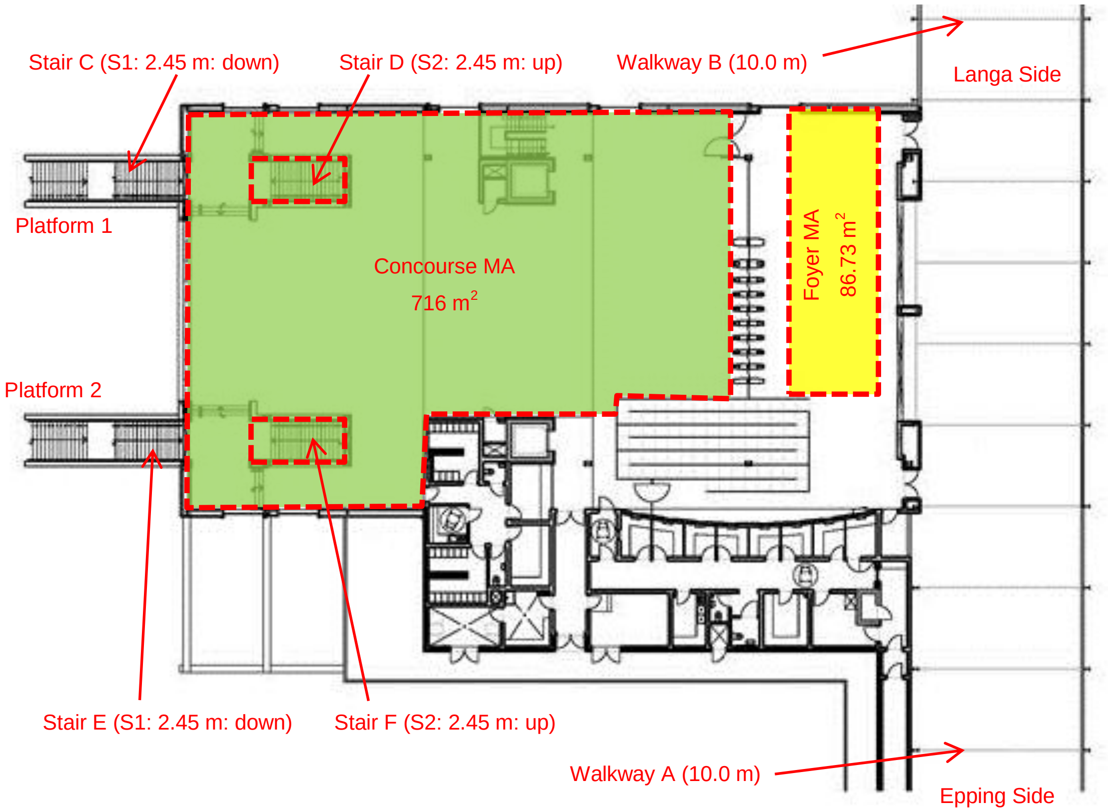


Figure 6.7: Concourse layout of Langa Station; (Source: J&B 2007)

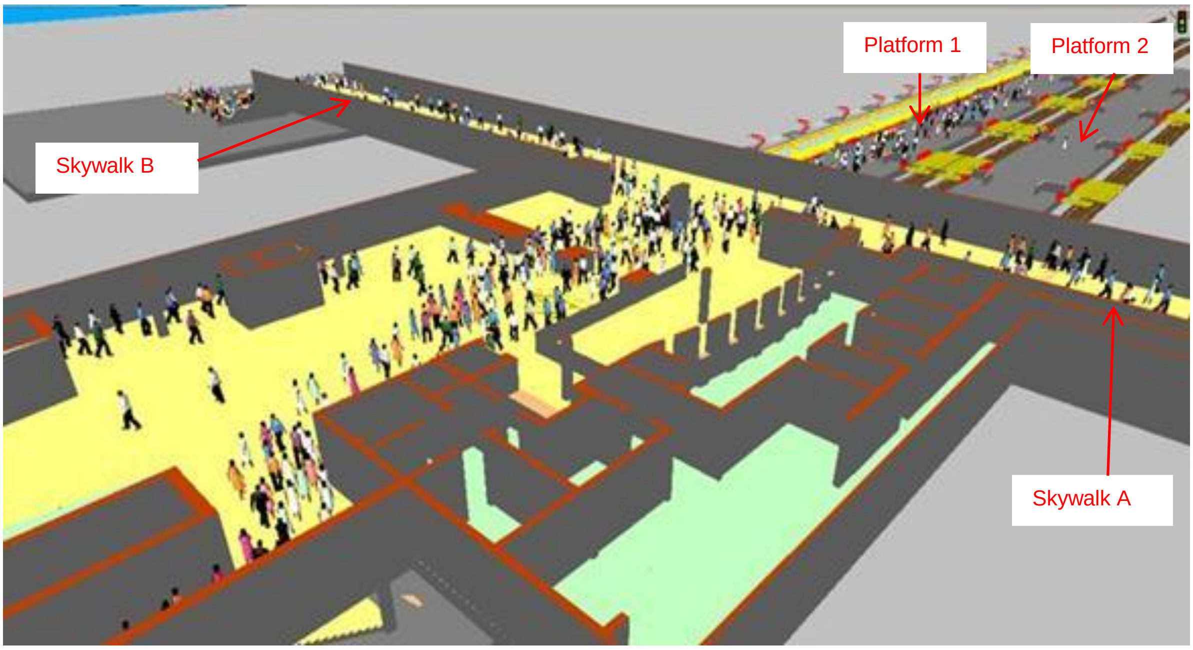


Figure 6.8: VISSIM output screenshot of Langa Station

6.4.2 Passenger Volumes

The future (2025) AM and PM peak 15-minute passenger volumes were based on peak period flows as determined by others (J&G 2008) for this station as indicated in Tables 6.5 and 6.6 respectively.

Table 6.5: Scenario 1 – AM peak train schedule and passenger volumes; (Goba 2009c)

Time (sec)	Direction	Plat/Line	Boarding (Pax)	Alighting (Pax)	Total (Pax)
540	From Cape Town	2/3	**57**	**75**	132
780	To Cape Town	2/4	**394**	**601**	995
960	To Cape Town	1/2	**441**	**412**	853
1140	To Cape Town	2/4	**202**	**362**	564
1260	To Cape Town	1/2	**335**	**554**	889
1320	From Cape Town	1/1	**98**	**113**	211
		Total	1,527	2,117	3,644
Street-to-street Volume : 11.3 pax/min					

For Scenario 1, it is modelled that 90% of boarding passengers originate from the Langa side and the remaining 10% from the Epping side. For the alighting process, 40% of all passengers proceeded to the Langa side and 60% proceeded to the Epping side.

Table 6.6: Scenario 2 – PM peak train schedule and passenger volumes; (Goba 2009c)

Time (sec)	Direction	Plat/Line	Boarding from South side* (Pax)	Alighting to North side* (Pax)	Total (Pax)
360	To Cape Town	2/4	**143**	**314**	457
540	From Cape Town	2/3	**291**	**535**	826
780	From Cape Town	1/1	**169**	**536**	705
1020	To Cape Town	1/2	**94**	**345**	439
1080	To Cape Town	2/4	**223**	**77**	300
1140	From Cape Town	2/3	**514**	**530**	1,044
1200	From Cape Town	1/1	**169**	**536**	705
		Total	1,603	2,873	4,476

Street-to-street Volume : 9.4 pax/min

**The south side is the Langa residential area whilst the north side is the employment zone (Epping Industrial area)*

For Scenario 2, it is modelled that 30% of boarding passengers originated from the Langa side and the remaining 70% from the Epping side. For the alighting process, 90% of all passengers proceeded to the Langa side and 10% proceeded to the Epping side.

6.4.3 Spatial Assessment Comparison

<u>SCENARIO 1</u>

The longitudinal outputs of Langa Station for Scenario 1 are included in Figures 6.9 and 6.10 and are indicated by plates E1 to E4 and plates F1 to F2 respectively.

Staircases:

Plates E1 and E2 show the comparative results of the longitudinal flow rate plots of combined staircases S1 and S2 on Platform 1 and combined staircases S1 and S2 on Platform 2 respectively. The individual S1 and S2 staircase outputs in this scenario have been combined since the VISSIM modelling technique employed uni-directional staircase operation with S1 (viz. stairs C and E) operating in the descending direction and S2 (viz. stairs D and F) operating in the ascending direction only. This was necessary as the VISSIM pedestrians became gridlocked on the stairs at high pedestrian volumes as "*streaming*"[50] did not occur.

The results shown in Plate E1 illustrate that both models predict worst case LOS E operational levels with the SP-model predicting a duration of 120 seconds and the micromodel predicting only 60 seconds duration in this LOS bandwidth. The micromodel graph again shows "*self-regulating*" phenomena exhibited through peak spreading resulting in the lower duration in the worst LOS bandwidth.

From the results shown in Plate E2, we again see that both models predict a worse case LOS E operation, except in this case, the SP-model predicts a shorter duration in this bandwidth (viz. 60 seconds) compared to the micromodel with a predicted duration of 120 seconds.

Skywalks:

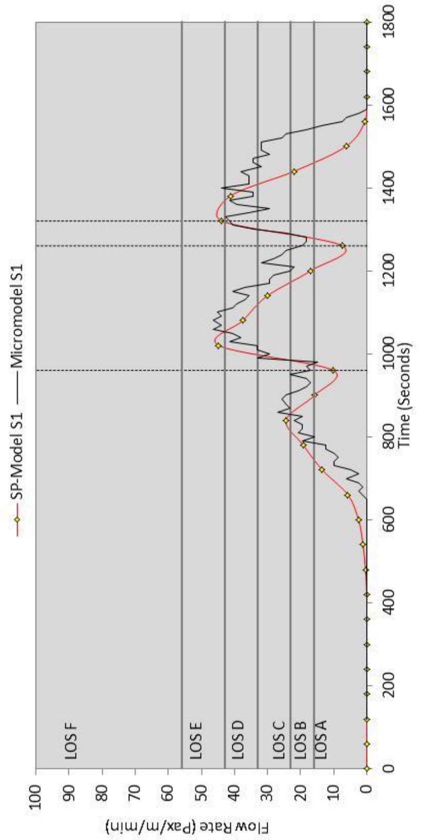
Plates E3 and E4 show the results of the comparative longitudinal flow rate plots of the Langa side skywalk (Side X) and the Epping side skywalk (Side Y). Apart from a brief 10-second occurrence in LOS B predicted by the micromodel shown in Plate E3, both models predict LOS A operational scenarios for both skywalk sides.

Foyer:

The results in Plate F1 in Figure 6.10 show the comparative longitudinal density plots of the foyer area. Both models predict a worst case LOS C operational scenario, except that the SP-model predicts a longer duration (viz. 200 seconds) than the micromodel (viz. 100 seconds) in this LOS bandwidth.

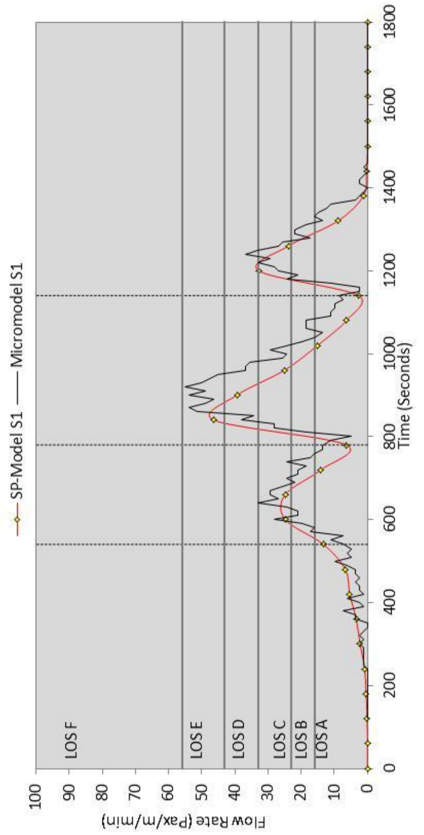
Concourse:

The results in Plate F2 show the comparative longitudinal density plots of the concourse area. For this scenario, the SP-model predicts a 256 second duration in the worst case LOS C bandwidth, compared to the micromodel results that predicts the entire concourse operation to fall within the LOS A bandwidth.



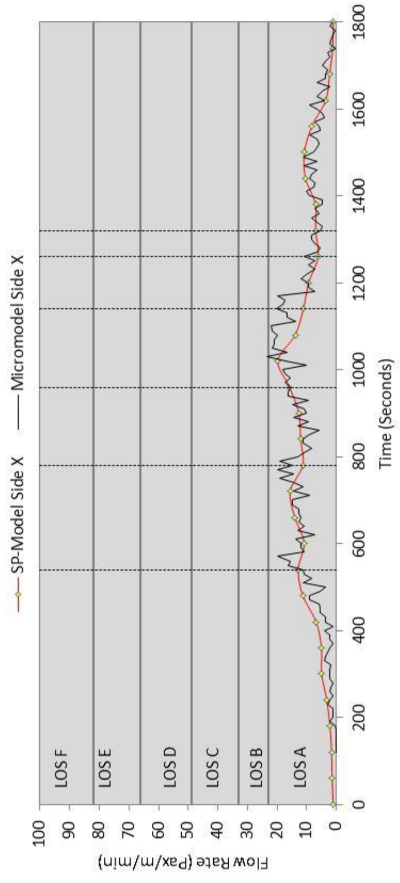
		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1260	180	120	120	120	0
	Total Time (%)	70.0%	10.0%	6.7%	6.7%	6.7%	0.0%
Micro Model	Total Time (sec)	1060	170	240	270	60	0
	Total Time (%)	58.9%	9.4%	13.3%	15.0%	3.3%	0.0%

E1: Platform 1, Staircases S1 & S2



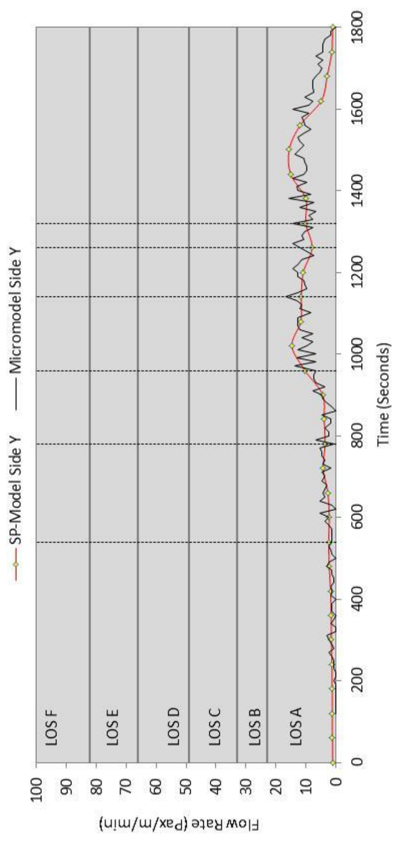
		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1380	0	300	60	60	0
	Total Time (%)	76.7%	0.0%	16.7%	3.3%	3.3%	0.0%
Micro Model	Total Time (sec)	1220	190	200	90	100	0
	Total Time (%)	67.8%	10.6%	11.1%	5.0%	5.6%	0.0%

E2: Platform 2, Staircases S1 & S2



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1790	10	0	0	0	0
	Total Time (%)	99.4%	0.6%	0.0%	0.0%	0.0%	0.0%

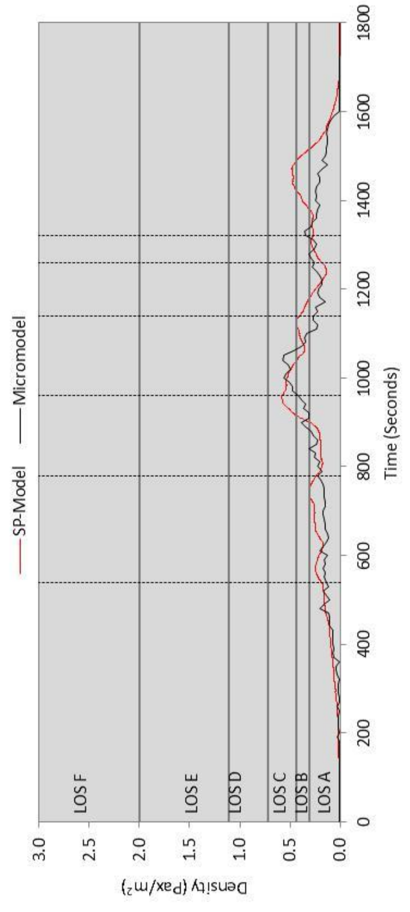
E3: Skywalk, Langa Side (Side X)



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

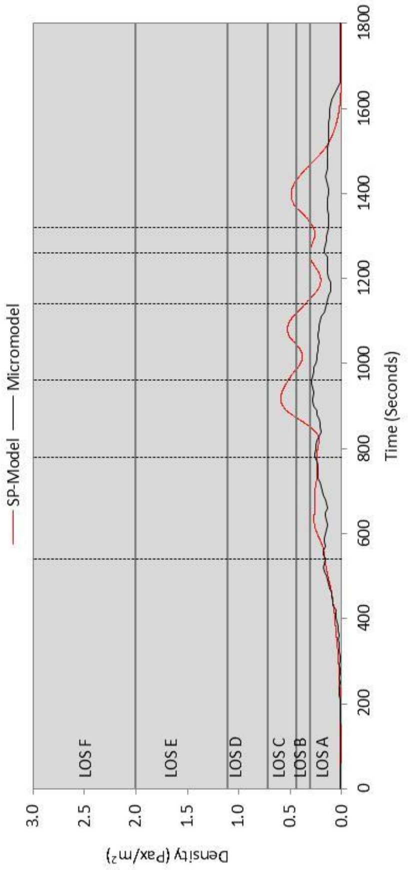
E4: Skywalk, Epping Side (Side Y)

Figure 6.9: Langa Station longitudinal flow rate plots: Scenario 1, Plate E



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1360	240	200	0	0	0
	Total Time (%)	75.6%	13.3%	11.1%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1540	160	100	0	0	0
	Total Time (%)	85.6%	8.9%	5.6%	0.0%	0.0%	0.0%

F1: Foyer Density Plot



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1340	204	256	0	0	0
	Total Time (%)	74.4%	11.3%	14.2%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

F2: Concourse Density Plot

Figure 6.10: Langa Station longitudinal density plots: Scenario 1, Plate F

SCENARIO 2

The longitudinal outputs of Langa Station for Scenario 2 are included in Figures 6.11 and 6.12 indicated by plates G1 to G4 and plates H1 to H2 respectively.

Staircases:

Plates G1 and G2 show the results of the longitudinal flow rate plots for the staircases. Plate G1 shows the combined S1 and S2 staircase plot for Platform 1. Both models predict a worst case LOS E performance with the SP-model predicting a duration of 120 seconds in this LOS bandwidth compared to the micromodel that predicts only a 50 second duration in this bandwidth.

Plate G2 shows the same resulting plot for the combined S1 and S2 staircases, but for Platform 2. The results in Plate G2 show that the SP-model predicts a worst case LOS E for a 120 second duration compared to the micromodel which predicts a worst case LOS F operation for a duration of 30 seconds.

Skywalk:

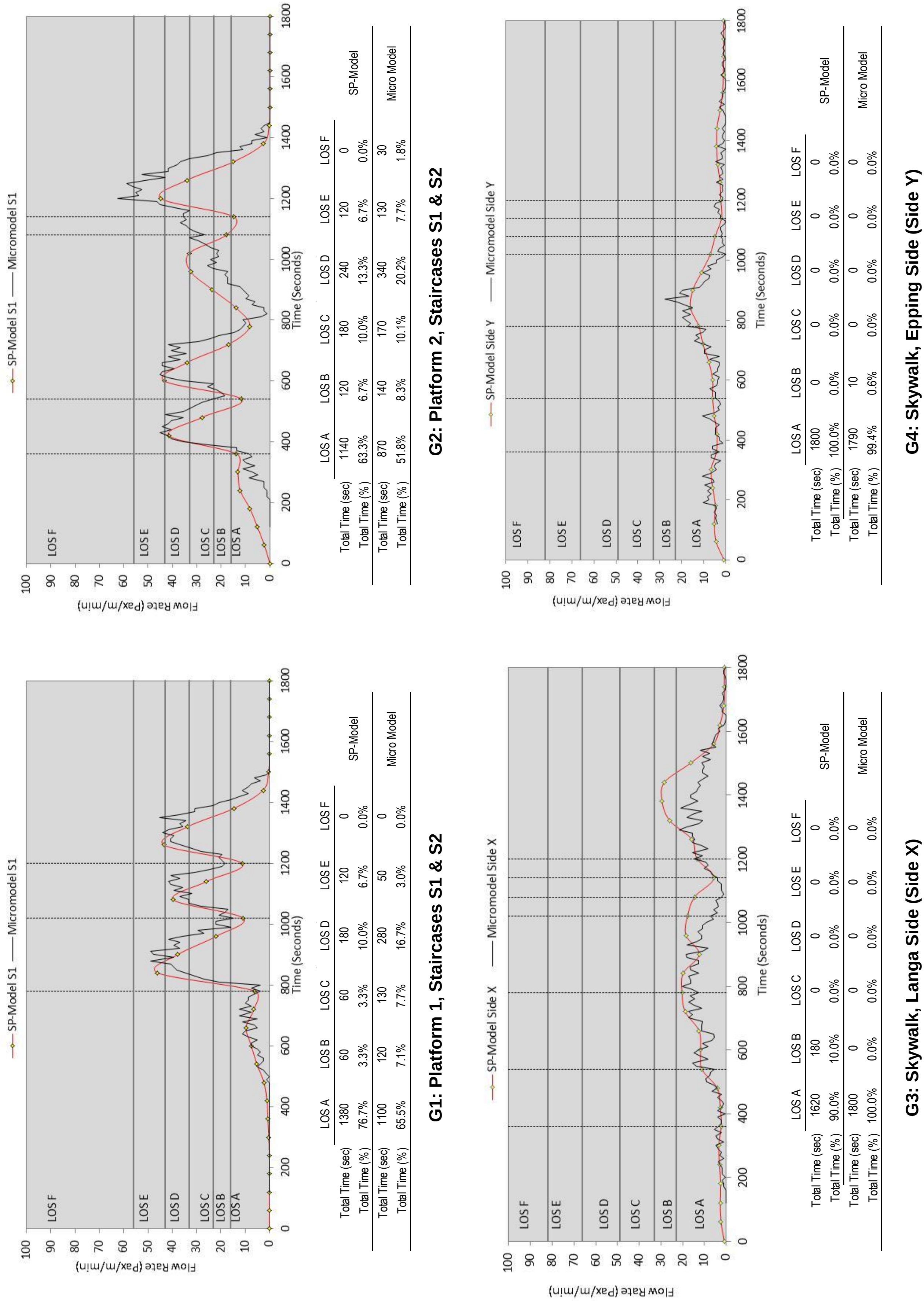
Plates G3 and G4 show the results of the longitudinal flow rate plots for the two sides of the skywalk. Plate G3 shows the output result comparison for the Langa side skywalk. For this side, the micromodel predicts the full operational scenario to operate within the LOS A bandwidth whilst the SP-model predicts a worst case LOS B operational scenario for a short 180 second duration. For the Epping side, Plate G4 shows that the SP-model predicts the full operational scenario within the LOS A bandwidth whilst the micromodel predicts a short duration of 10 seconds within LOS B bandwidth.

Foyer:

Plate H1 in Figure 6.12 shows the results of the longitudinal density plots for the foyer area. Both models predict a worst case LOS C operational scenario with the SP-model predicting a duration of 376 seconds in this LOS bandwidth compared to a shorter 190 second duration predicted by the micromodel.

Concourse:

Plate H2 shows the results of the longitudinal density plots for the concourse area. Again, both models predict a worst case LOS C operational scenario with the SP-model predicting a duration of 348 seconds in this bandwidth compared to a shorter 60 second duration in this bandwidth predicted by the micromodel.



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1380	60	60	180	120	0
	Total Time (%)	76.7%	3.3%	3.3%	10.0%	6.7%	0.0%
Micro Model	Total Time (sec)	1100	120	130	280	50	0
	Total Time (%)	65.5%	7.1%	7.7%	16.7%	3.0%	0.0%

G1: Platform 1, Staircases S1 & S2

		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1140	120	180	240	120	0
	Total Time (%)	63.3%	6.7%	10.0%	13.3%	6.7%	0.0%
Micro Model	Total Time (sec)	870	140	170	340	130	30
	Total Time (%)	51.8%	8.3%	10.1%	20.2%	7.7%	1.8%

G2: Platform 2, Staircases S1 & S2

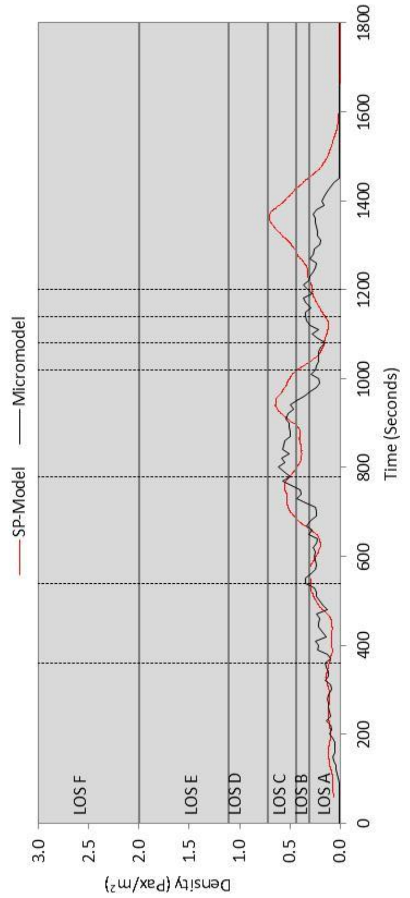
		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1620	180	0	0	0	0
	Total Time (%)	90.0%	10.0%	0.0%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

G3: Skywalk, Langa Side (Side X)

		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1800	0	0	0	0	0
	Total Time (%)	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1790	10	0	0	0	0
	Total Time (%)	99.4%	0.6%	0.0%	0.0%	0.0%	0.0%

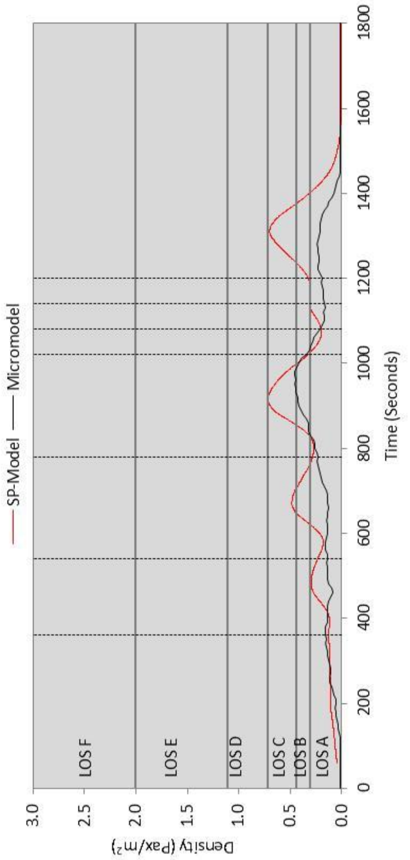
G4: Skywalk, Epping Side (Side Y)

Figure 6.11: Langa Station longitudinal flow rate plots: Scenario 2, Plate G



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1181	243	376	0	0	0
	Total Time (%)	65.6%	13.5%	20.9%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1430	180	190	0	0	0
	Total Time (%)	79.4%	10.0%	10.6%	0.0%	0.0%	0.0%

H1: Foyer Density Plot



		LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
SP-Model	Total Time (sec)	1199	253	348	0	0	0
	Total Time (%)	66.6%	14.1%	19.3%	0.0%	0.0%	0.0%
Micro Model	Total Time (sec)	1600	140	60	0	0	0
	Total Time (%)	88.9%	7.8%	3.3%	0.0%	0.0%	0.0%

H2: Concourse Density Plot

Figure 6.12: Langa Station longitudinal density plots: Scenario 2, Plate H

6.4.4 Statistical ARIMA Assessment

The results of the ARIMA time-series model evaluation used to test the statistical correlation of the two models is indicated in Table 6.7 below. As already indicated, the statistical testing has been independently conducted by the Centre for Statistical Consultation at the University of Stellenbosch.

Table 6.7: ARIMA results for Langa station

	Plate	Setting*	Model	*P*-Statistic				Conclusion
				Constant (*c*)	*q*(1)	*q*(2)	*q*(*n*)	
Scenario 1	E1	l1p1s1+s2	AR(5)	0.420	0.425	0.056	0.032 at *n*=5	Model correlates
	E2	l1p2s1+s2		Data cannot be calculated				Cannot use ARIMA
	E3	l1sx	MA(1)	0.654	0.004	-		Model correlates
	E4	l1sy	MA(1)	0.564	0.000	-		Model correlates
	F1	l1f	ARMA(1,1)	0.111	0.531	0.000		Model correlates
	F2	l1c	ARMA(1,1)	0.384	0.007	0.000		Model correlates
Scenario 2	G1	l2p1s1+s2	ARMA(1,1)	0.507	0.041	0.132		Model correlates
	G2	l2p2s1+s2		Data cannot be calculated				Cannot use ARIMA
	G3	l2sx	AR(1)	0.058	0.000	-		Model correlates
	G4	l2sy	MA(1)	0.510	0.000	-		Model correlates
	H1	l2f	MA(1)	0.123	0.000	-		Model correlates
	H2	l2c	AR(1)	0.121	0.000	-		Model correlates

** Settings Legend:*

l1 or l2: Langa station scenarios 1 or 2

p1 or p2: platforms 1 or 2

s1+s2: combined width of staircases 1 and 2

f: foyer

c: concourse

sx or sy: skywalk side x or y

Table 6.7 shows the various types of ARIMA models that were applied for the testing. All scenario tests, except “l1p2s1+s2” (Plate E2) in Scenario 1 and “l2p2s1+s2” (Plate G2) in Scenario 2 could be assigned an ARIMA model. Apart from these two tests, all other tests proved that the Null hypothesis, as defined in Subsection 6.3.4, is true and therefore that there is a statistical correlation between the SP-model and the microscopic model results.

6.4.5 Conclusions

For most of the results for the Langa station case study, the longitudinal density plots were found to provide worse LOS results than the flow rate graphs. As already discussed, this is to be expected, with worse density LOS results than flow rate LOS results for the same infrastructure due to the "*LOS mismatch*" phenomena (refer to Figure 4.28 in Subsection 4.4.1).

Table 6.8 summarises the Langa station results for the worst LOS values obtained during the modelling analysis using both models. As in the previous case study, the results shown in bold italics indicate where ARIMA testing could not be undertaken and where a correlation between the two models could therefore not be verified.

Table 6.8: Comparison of worst case model results for Langa station

Infrastructure	Item	Platform	Scenario 1		Scenario 2	
Model			**VISSIM**	**SP-Model**	**VISSIM**	**SP-Model**
Period			**AM**		**AM**	
Assessment year			2025		2025	
Street-to-street included ?			Yes	Yes	Yes	Yes
Staircases	S1+S2 (C + D)	1	E (60 sec)	E (120 sec)	E (50 sec)	E (120 sec)
	S1+S2 (E + F)	2	***E (100 sec)***	***E (60 sec)***	***F (30 sec)***	***E (120 sec)***
Skywalk	A (X)	n/a	A (1800 sec)	A (1800 sec)	A (1800 sec)	B (180 sec)
	B (Y)	n/a	A (1800 sec)	A (1800 sec)	B (10 sec)	A (1800 sec)
Foyer	n/a	n/a	C (100 sec)	C (200 sec)	C (190 sec)	C (376 sec)
Concourse	n/a	n/a	A (1800 sec)	C (256 sec)	C (60 sec)	C (348 sec)

The platform-to-concourse staircases were found to operate by both models at poor levels-of-service for the predicted 2025 passenger volumes (i.e. at LOS E) for both scenarios. Apart from stairs (E + F) the SP-model predicted longer durations within the LOS E bandwidth. For stairs (E + F), the converse occurred where the micromodel predicted longer durations in LOS E for Scenario 1 and a short duration in LOS F for Scenario 2.

The microsimulation results were adequately represented by the results of the SP-model but as with the Century City results, the SP-model predicted marginally more pessimistic LOS density values for the foyer and concourse infrastructure items.

6.5 Comparison of SP-model results against Macroscopic Calculation Method

This section compares the SP-model results obtained for the various case scenario stations against the results from macroscopic calculation methods currently used in South Africa. Table 6.9 shows the comparison of the results between the two approaches for the Century City Station, Scenario 1.

Table 6.9: Comparison of SP-model results versus macroscopic results for Century City station (Scenario 1)

Infrastructure	Actual	SP-model	Macroscopic Calculation
Foyer Area	99.16 m^2	C (58 sec)	99.16/(1025 ÷15) = 1.45 m^2/pax = LOS C
Concourse Area	291 m^2	B (52 sec)	291/(1025 ÷15) = 4.26 m^2/pax = LOS A
Skywalk width	4.2 m	C (60 sec) A (15 min)	(1025 ÷15)/4.2 = 16.27 pax/m/min = LOS A
Platform stairs	2 x 2.0 m	D (60 sec)	(1025 ÷15)/(2 x 2.0) = 17.08 pax/m/min = LOS B

The table shows that, apart from the Foyer area results, the macroscopic calculation yields more optimistic levels-of-service results than the SP-model results. Scenario 2 was not calculated using the macroscopic approach as this tested simultaneous train arrivals only. Table 6.10 shows the comparison of the results between the two calculation methods for Langa Station, for both scenarios 1 and 2.

Table 6.10: Comparison of SP-model results versus macroscopic results for Langa station (Scenario's 1 & 2)

Scenario 1: AM Peak			
Infrastructure	**Actual**	**SP-model**	**Macroscopic Calculation**
Foyer Area	86.73 m^2	C (200 sec)	86.73/(3644 ÷15) = 0.36 m^2/pax = LOS F
Concourse Area	716 m^2	C (256 sec)	716/(3644 ÷15) = 2.9 m^2/pax = LOS B
Skywalk width	10.0 m	A (15 min)	(3644 ÷15)/10 = 24.3 pax/m/min = LOS B
Platform stairs	4 x 2.45 m	E (60 - 120 sec)	(3644 ÷15)/(4 x 2.45) = 24.8 pax/m/min = LOS C
Scenario 2: PM Peak			
Infrastructure	**Actual**	**SP-model**	**Macroscopic Calculation**
Foyer Area	86.73 m^2	C (376 sec)	86.73/(4476 ÷15) = 0.29 m^2/pax = LOS F
Concourse Area	716 m^2	C (348 sec)	716/(4476 ÷15) = 2.4 m^2/pax = LOS C
Skywalk width	10.0 m	A (15 min) B (180 sec)	(4476 ÷15)/10 = 29.8 pax/m/min = LOS B
Platform stairs	4 x 2.45 m	E (120 sec)	(4476 ÷15)/(4 x 2.45) = 30.4 pax/m/min = LOS C

For Scenario 1, the table shows that, apart from the Foyer area and Skywalk results, the macroscopic calculation yields more optimistic levels-of-service than the SP-model results. For Scenario 2, the table shows comparable results for the Concourse area and Skywalk width but the macroscopic calculation reveals more pessimistic Foyer area levels-of-service, but a more optimistic Platform staircase operation.

The inconsistent variation between results of the two methods is considered intuitive due to the effect of the "*micro-peaking*" effects discussed in Subsection 2.1.4 which is not considered in the macroscopic approach, where flow rates are aggregated over 15 minutes, irrespective of train scheduling.

6.6 Concluding Discussion

This chapter has described the results of the SP-model developed towards satisfying one of the main objectives of this dissertation. The model has been used to assist in determining pedestrian spatial requirements in concourse railway stations and has been tested and compared against the results of the VISSIM microscopic analysis undertaken for two case scenario stations in Cape Town, South Africa.

From the visual and statistical assessment of the results presented in the previous sections, it has been demonstrated that the SP-model is able to provide acceptable "*first-order*" results of the pedestrian levels-of-service on a longitudinal (time-series) basis. The SP-model therefore fills the gap between heuristic design and detailed microscopic modelling. It was not the intention (nor possible) for the SP-model to exactly replicate the results of the microscopic modelling, but the comparative analysis made in the previous sections indicate that the results are promisingly closer to the microscopic results than expected for certain infrastructure types, particularly the staircases and skywalks.

Future improvements to the model, incorporating turnstile delay for example, could improve the comparative outputs for the concourse and foyer results, which were found to be always more conservative than the microscopic results. Apart from the representative results achieved, the time involved in setting up a SP-model compared to a microscopic model is in the order of 1:15 further enhancing the practicality of the model, especially as the type of input required for the SP-model is not extensive and specialist modelling expertise or knowledge is not required. Furthermore, the SP-model allows for quick design changes supporting an iterative station design process. Future improvements to the model should not sacrifice model simplicity for unnecessary accuracy.

Using the methods and techniques employed within this research, it is the intention that new station designs should not have spatial inadequacies, which can be avoided by incorporating the pedestrian analysis results provided by the SP-model. Earlier versions of the SP-model (i.e. the SP-matrix) have already been applied successfully in several transportation studies, including the new Moses Mabhida station (Arup 2008) in Durban, KwaZulu-Natal and the upgraded Khayelitsha (Arcus Gibb 2008a) and Nyanga stations (Arcus Gibb 2008b) located in Cape Town.

The SP-model is best suited to be used in the early planning phases (when detailed plans have not yet been produced or finalised and where the number of stairs, width of stairs, skywalks etc. can still be amended). The SP-model can however also be used (by clients) as a detail design check (when more detailed plans are drawn) and during the operational stage (for identification of problem areas). In conclusion, the case study examples have shown that the SP-model is effective at calculating longitudinal LOS for various station infrastructure types and can therefore be applied as a "*first order*" station design assessment tool.

7. CONCLUSIONS AND RECOMMENDATIONS

The main research theme in this study relates to pedestrian behaviour within South African railway stations, the observation of this behaviour and the application of this empirical data towards the development of a spreadsheet SP-model. This final chapter summarises the main results of the research. First, an overview of the main findings of the study is made, followed by some of the research limitations before the main conclusions are presented. Next, implications of the research from both a theoretical and practical significance are presented, and finally recommendations for future research are proposed.

7.1 Summary of Findings

This section provides a brief overview of the main findings made in the study before the limitations and conclusions are presented in the following sections. This dissertation presents the development of the SP-model (discussed in Chapter 5) for the evaluation of pedestrian space requirements within railway stations. The need for such a simple model was motivated in Chapter 1 and the theoretical framework of the model has been based on a broad literature survey (discussed in Chapter 2) and new observations and empirical findings (discussed in chapters 3 and 4). The functionality assessment of the model was conducted through case studies described in Chapter 6.

Due to the limited knowledge available on pedestrian behaviour within railway station facilities in this country, new empirical data was collected as part of this research. This permitted the analyses of local pedestrian characteristics and flow composition of pedestrian walking behaviour, pedestrian behaviour on platforms, stairs and skywalks of a train station, as well as boarding and alighting behaviour. As part of the data capture process, a video-tracking method was developed to track individual pedestrians.

The observations produced new local results with respect to free and constrained speed distributions, speed variances, fundamental diagrams (including influences of bi-directional flows), B&A behaviour and capacities of infrastructure. These results constitute important improvements considering the lack of existing local knowledge. The resulting empirical data has not only been used to generate input for the SP-model (discussed in Chapter 5), but also extends existing theories on pedestrian walking behaviour, in particular the impact of flow ratios on flow rates and walking speeds. The functionality assessment of the SP-model (discussed in Chapter 6) was based on the application of the model to two new railway station designs in Cape Town, South Africa, where the SP-model output predictions were compared to microscopic (VISSIM) output simulation results.

Within this dissertation and associated papers[e] submitted by the author since 2009, this research has demonstrated the impact of a number of the pedestrian behavioural issues within local railway station environments. New local empirical data has been provided, together with methods of gaining field data incorporating these issues. The results of the empirical data can now be used by designers and modellers for the assessment of future station designs with similar pedestrian mixes.

[e] Refer to Biography (page vii) for a full list of conference papers and articles submitted.

A number of the more important issues and findings identified in this study are listed below. Relevant subsection references are indicated within superscripted parenthesis after each finding/conclusion statement:

- From the literature review, it emerged that the local station design guideline documentation recommends LOS B AFV/APAO design criteria for station walkways and queuing areas which is considered too onerous. Furthermore, the guideline recommends a LOS D requirement for entrance/exit doorways, which is considered too pessimistic for design purposes. [(2.1.2)]

- The literature review, which together with the author's experience, revealed that there are no set station design methods or procedures proposed in local station design guideline documentation. This leads to ambiguous assessment techniques used by practitioners in the determination of station functional areas. Without a reliable method for estimating pedestrian capacities, design of new facilities does not follow uniform design processes, resulting in high levels of uncertainty in determining if the time, money and resources invested in upgrading facilities will actually cater to the demand.[(2.1.3)]

- Is was shown that the general macroscopic rules-of-thumb for determining peak passenger loads are inadequate and misleading for detailed design purposes. The process of identifying the design peak one-minute pedestrian volume by dividing the peak 15-minute flow by 15 advocated in certain design guideline documents is erroneous and ignores the "*micro-peaking*" effects that typically occur within railway station environments. It was shown that "*micro-peaking*" volumes can be as much as 72% greater than the uniform flow rate lasting for up to three minutes duration and can lead to the under-design of facilities.[(2.1.4 & 6.5)]

- The average walking speed ($\bar{u}$) of pedestrians (n = 2,783) observed on platforms for the entire range of densities was found to be 1.19 m/s with a standard deviation of 0.514 m/s.[(4.2.1)] On Skywalks, the average walking speed was slower at 1.11 m/s (n = 12,491) for the entire range of densities with a standard deviation of 0.384 m/s.[(4.2.2)] The combined average ascending and descending horizontal walking speed on stairs was found to be 0.55 m/s (n = 9,988) for the entire range of densities with a standard deviation of 0.212 m/s. This combined average horizontal walking stair speed tends to lie towards the bottom of the range of free walking speeds of other international studies. [(4.2.3)]

- The average walking speed ($\bar{u}$) of male pedestrians (n = 1,431) observed on *platforms* for the entire range of densities was found to be 1.29 m/s with a standard deviation of 0.597 m/s. For females (n = 1,352), the average walking speed was found to be **15.5%** less than the male average walking speed at only 1.09 m/s with a standard deviation of 0.382 m/s. [(4.3.1)]

- The average walking speed ($\bar{u}$) of male pedestrians (n = 7,166) observed on *skywalks* for the entire range of densities was found to be 1.19 m/s with a standard deviation of 0.426 m/s. For females (n = 5,325), the average walking speed was found to be **15.1%** less than the male average walking speed at only 1.01 m/s with a standard deviation of 0.291 m/s. [(4.3.1)]

- The average horizontal walking speed ($\bar{u}$) of male pedestrians (n = 6,892) for both the ascending and descending direction observed on *stairs* for the entire range of densities was found to be 0.57 m/s with a standard deviation of 0.234 m/s. For females (n = 3,096), the average walking speed was found to be **12.8%** less than the male average walking speed at only 0.497 m/s with a standard deviation of 0.140 m/s. (4.3.1)

- The results of the empirical research conducted on *platforms* revealed that person size significantly affected average walking speeds. When considering the entire population (n = 2,783), the average walking speed ($\bar{u}$) of leaner/smaller built persons was found to be 1.33 m/s and that of larger built persons was found to be 23.3% slower at 1.02 m/s. When isolating the data by gender, leaner/smaller built males were found to walk at an average of 1.49 m/s and that of larger built males was found to be 20.1% slower at 1.19 m/s. Leaner/smaller built females were found to walk **19.5%** slower than similar sized men at an average of 1.20 m/s and that of larger built females was found to be **17.7%** slower than similar sized men at 0.98 m/s. Despite the biased distribution of the female population towards the larger frame with the distribution of the male population biased towards the leaner frame, the percentage difference in walking speeds across genders was found to be similar for all person sizes. (4.3.2)

- The overall *platform* dataset (n = 2,783) including both genders, revealed that pedestrians who walked alone, did so at an average speed of 1.22 m/s compared to those walking in groups of two with an average walking speed of 1.02 m/s and those walking in groups of three or more, who were observed to walk even slower at an average walking speed of 0.92 m/s. The difference between the average walking speeds of singletons and those walking in groups of two is calculated to be **16.4%**. This is significantly more than the 3.0 to 10.5% drop in average walking speed reported by other researchers. (4.3.3)

- The average speed of females walking alone on *platforms* was observed to be 1.11 m/s compared to male singletons who were observed to walk **18.9%** faster at an average walking speed of 1.32 m/s. The observed average walking speed for female groups of two or more was 1.00 m/s and that for male groups was however observed to be only 3% faster, calculated at 1.03 m/s. (4.3.3)

- For the observations made on *platforms*, it was observed that the average walking speeds of pedestrians carrying luggage were significantly affected. Unencumbered pedestrians (n = 383) walked fastest at 1.34 m/s followed by those pedestrians wearing a rucksack with both straps over the shoulders (n = 213) at 1.26 m/s. Pedestrians who were observed to carry baggage/parcels in both hands (n = 18) were found to walk the slowest at 1.07 m/s. Pedestrians who walked carrying luggage in one hand (n = 513) were observed to walk at average speed of 1.22 m/s. In these observations, a difference of 8.96% is calculated between unencumbered and pedestrians carrying luggage in one hand. This correlates with more recent research findings where a similar drop between unencumbered pedestrians and pedestrians carrying large bags was observed. (4.3.4)

- From the *platform* empirical dataset, an average 'waiting' walking speed of 1.04 m/s (n = 788) and an average alighting walking speed of 1.24 m/s (n = 1,888) is calculated, a difference of 19.2% which corroborates with another similar study conducted in Holland. It was concluded that the high boarding speed of 1.54 m/s (*n* = 107) observed in this study is as a result of individual pedestrian anxiety due to the possibility of not boarding due to the high passenger boarding demand and high coach occupancy levels. (4.3.5)

- The *platform* observations revealed statistically significant differences between morning (AM) and afternoon (PM) peak average walking speeds for Bonteheuwel Station as well as significant differences across station locations for the morning peak results. For all infrastructure types combined, the average AM and PM peak period walking speeds at Bonteheuwel Station was found to be 1.33 m/s and 1.15 m/s respectively, with the lowest overall average walking speed of 1.11 m/s recorded for the AM peak period at Maitland Station. (4.3.6)

- The results of the *platform* observations revealed that there are statistically significant differences in average walking speeds at different station locations, for the same time period even when isolating variables for both gender types. It was found that there is an insignificant difference between average male walking speeds when compared across peak time periods (AM versus PM peaks) at the same station location. The observations made in this study confirm that location influences walking speeds for all gender types. It was found that time periods (whether AM or PM peak) have a similar significant impact on walking speeds, except for the male gender types where the impact at Bonteheuwel Station, as already indicated, was found to be insignificant. (4.3.6)

- The results of the *skywalk* observations revealed that the pedestrians at Bonteheuwel Station walked, on average, 15.45% faster than those pedestrians observed at Maitland Station. This difference (viz. 1.23 m/s versus 1.04 m/s) was found to be statistically significant. It was also found that all pedestrians walked, on average, significantly faster on skywalks during the PM period ($\bar{u}$ = 1.16 m/s) than during the AM period ($\bar{u}$ = 1.07 m/s), a difference of **7.76%**. (4.3.6)

- From the results of the *staircase* observations, it was observed that all pedestrians walked significantly faster on average (for both ascending and descending directions) during the PM peak period ($\bar{u}$ = 0.56 m/s) than the AM peak period ($\bar{u}$ = 0.52 m/s), a difference of **7.14%**, similar to that observed for the skywalk data. (4.3.6)

- For the *staircase* dataset, when the time period, gender and direction of movement variables are isolated, it was observed that the differences in average walking speed between the ascending movements (viz. 0.55 m/s for males and 0.46 m/s for females) and descending movements (viz. 0.53 m/s for males and 0.46 m/s for females) between the same gender types in the AM peak is not large (Δ = 0.02 m/s) and in fact was equal for the female gender group. (4.3.6)

- The results of the passenger arrival rate (*PAR*) observations revealed that, on average for *n* = 2,872 passengers observed boarding 14 trains, a greater proportion of passengers (i.e. 85% of the total boarding passenger volume) arrived on the platform within four minutes prior to train arrival with fewer passengers arriving (i.e. 15% of the total boarding passenger volume) more than four minutes before train arrival. (4.3.7 & 5.3.2)

- The results of the flow (q) vs. density (k) relationship for the *skywalk* corresponded to a parabolic curve function with a maximum flow rate capacity (q_c) observed at 1.13 pax/m/s observed at a critical density (k_c) of 2.53 pax/m^2. A similar curvilinear relationship was exhibited for movement on *stairs* but despite a high sample rate (n = 8,244), a maximum flow rate was not observed with maximum 99th percentile flow rate capacities of 0.873 pax/m/s and 0.959 pax/m/s observed for the ascending and descending stair movement respectively, neither occurring at critical densities. (4.4.1)

- Average free-flow speeds ($\bar{u}_f$) observed for *skywalks* within the LOS A density criteria calculated to 1.33 m/s which is only slightly lower than the average free-flow speed of 1.36 ± 0.13 m/s identified from the international literature. For *stairs*, the average horizontal free-flow speed calculated to 0.80 m/s and 0.77 m/s for the descending and ascending direction respectively. Average free-flow speeds observed for *platforms* was the highest at 1.36 m/s. (4.4.1 & 4.4.5)

- The development of the flow rate (q) vs. density (k) relationship for *skywalks* when compared to the TCQSM LOS criteria (TRB 1999) revealed a "*LOS-mismatch*" with differences in the corresponding LOS flow rate criteria of between 21% to 36% lower than that proposed by the TCQSM criteria. From our observations, it is recommended that HCM 2000 flow rate criteria be used for local conditions as follows: (4.4.1 & 4.4.4)

Table 7.1: Proposed revised LOS criteria for level walkway infrastructure

LOS	APAO	AFV
	Space-density M (m^2/pax)	Flow rate q (pax/m/min)
A	> 3.3	< 14
B	2.3 – 3.3	14 – 21
C	1.4 – 2.3	21 – 33
D	0.9 – 1.4	33 – 49
E	0.5 – 0.9	49 - 60

- The development of the flow rate (q) vs. density (k) relationship for *stairs* when compared to the TCQSM LOS criteria (TRB 1999) also revealed a "*LOS-mismatch*" phenomena, but with greater differences in the corresponding LOS flow rate criteria of between 35% to 45% lower than that proposed by the TCQSM criteria. From our observations, it is recommended that new flow rate criteria data be used for local conditions as follows: (4.4.1 & 4.4.4)

Table 7.2: Proposed revised LOS criteria for stair infrastructure*

LOS	APAO	AFV
	Space-density M (m^2/pax)	Flow rate q (pax/m/min)
A	> 1.9	< 10
B	1.4 – 1.9	10 – 13
C	0.9 – 1.4	13 – 20
D	0.7 – 0.9	20 – 23
E	0.4 – 0.7	23 – 48

**For stairs: Riser = 160 mm, tread = 300 mm and slope angle = 27.89^o*

- It was observed that the AFV design LOS criteria values proposed in the NGS (SARCC 1997) guidelines matched the LOS criteria values as specified in the TCQSM (TRB 1999) guidelines and therefore do not consider the observed "*LOS-mismatch*" phenomenon. This exercise therefore confirmed the author's prior preference for using the APAO density (*k)* evaluation criteria over the AFV (*q*) criteria for design purposes; or using the AFV (*q*) criteria only when the local pedestrian dynamic relationship has been studied and fully understood, as undertaken in this study, with revised AFV criteria recommended in Tables 7.1 or 7.2. (4.4.4)

- The results of the walking speed (*u*) vs. density (*k*) relationships for all infrastructure types revealed statistically significant relationships with average speeds linearly decreasing with increasing density in all cases. Also observed was the greater variation in walking speed (*u*) data at low densities with little walking speed variance for densities greater than 1.0 pax/m^2 on platforms and 2.0 pax/m^2 on skywalks and stairs, which is attributable to the ability of pedestrians to select their preferred walking speed at free-flow conditions, which they are unable to do under congested conditions. (4.4.2)

- The results of the speed (*u*) vs. flow rate (*q*) relationships for both the *skywalk* and *stair* infrastructure types revealed that whilst the fundamental curves would suggest a parabolic curve opening onto the y-axis (walking speed), the curve plotted for both datasets did not entirely abide to this shape despite the high sample rate (*n* = 12,491 for skywalks and *n* = 8,244 for stairs). In both cases, unlike the *q* vs. *k* graphs, the maximum flow rate (q_c) could not be determined from this relationship. (4.4.3)

- For the *skywalk* dataset, a 92.3% drop in the maximum flow rate (q_{max}) from 1.69 pax/m/s to around 0.13 pax/m/s for a flow ratio drop from *r* = 1.0 to 0.1 was observed which corroborates a reported drop of 90% obtained by other researchers. For *staircases*, a maximum flow rate (q_{max}) drop from 0.93 pax/m/s to around 0.09 pax/m/s was observed for the same flow ratio drop, viz. a 90.3% drop in the particular <u>uni-directional</u> flow rate. (4.4.6)

- It was observed that the total maximum *skywalk* <u>bi-directional</u> capacity reduced from 98.25 pax/m/min at *r* = 1.0 to 95.10 pax/m/min at *r* = 0.9, a drop of 3.21%. A higher drop of 6.09% (from 61.76 pax/m/min to 58.00 pax/m/min) is observed for *stairs* from *r* = 1.0 to 0.9. From *r* = 0.9 to 0.5, a drop of 12.83% and 27.81% is calculated for the skywalk and stairs respectively. From these results, it was found that the impact of flow ratio on capacity is more than double on stairs than on level terrain viz. skywalks. (4.4.6)

- The results of the observations on both *stairs* and *skywalks* revealed a lower influence of flow ratio (*r*) on maximum <u>bi-directional</u> capacity flow rates from *r* = 1.0 to 0.9 than proposed by other researchers. It is proposed that the reason for this is that a greater degree of bodily contact is considered acceptable in the South African context and hence the impact of the minor flow on capacity is far less than in developed countries where pedestrians try maintain greater interpersonal distances despite crowded conditions. (4.4.6)

- By isolating the density (*k*) criteria in determining the impact of flow ratio (*r*) on average walking speed ($\bar{u}$), the observations confirmed that there is no significant difference or variation between average walking speeds for level terrain (viz. skywalks) and staircase movement under various flow ratios (*r*) at capacity conditions (viz. LOS E). Due to the limited observations made at LOS A and B, a similar conclusion could not be confirmed for free-flow conditions but the indication, based on the overall $\bar{u}$ versus *r* relationship for all densities, seems to suggest that average speed is not affected by flow ratio at free-flow conditions. Further investigations/studies is recommended to confirm this observation at other LOS densities. (4.4.7)

- From the boarding and alighting dataset, it was found that 92% of the B&A observations conformed to the predominant Type 3 B&A behaviour where the boarding process followed the alighting process. Of this, 39.4% of the B&A observations showed simultaneous B&A activity for durations lasting between one and three seconds. B&A observations showing a short interval (or time delay) between alighting and boarding accounted for 30% of the observations and alighting behaviour followed immediately by boarding (i.e. no delay) occurred for 30.6% of the observations. (4.5.1)

- A mean alighting rate (*AT*/pax) of 0.64 ± 0.24 sec/pax was observed for alighting passengers and a boarding rate (*BT*/pax) of 1.34 ± 0.78 sec/pax was observed. It was also observed that both boarding and alighting rates decreased slightly with increasing boarding or alighting passenger volumes respectively. (4.5.4)

- The B&A data revealed that increasing boarding/alighting volumes (i.e. increasing *R* values) gradually increases the alighting time per passenger (*AT*/pax) from 0.62 sec/pax at R = 1.0 to 1.25 sec/pax at R = 60. The increase in the *R*-ratio was found to improve the boarding rate per passenger (*BT*/pax) from 1.36 sec/pax at R = 1.0 to 0.85 sec/pax at R = 60. Although the correlation trend agrees in principle to the simulations made by other researchers, the correlation for the boarding data was not found to be statistically significant due to the clustering of the data points at $R < 10$. Although the alighting data relationship was found to be statistically significant, very poor correlation coefficients ($R^2 < 0.1$) were calculated for both boarding and alighting datasets. It is argued that the main reason for the poor correlation is the sensitivity of the ratio *R* for very low boarding volumes associated with higher alighting volumes that reduces the accuracy of the linear approximation. (4.5.4)

- The average 0.64 sec/pax alighting rate (*AT*/pax) observed in this study was found to be the lowest of all the international literature alighting rates reviewed but the observed 0.20 to 2.00 sec/pax range coincided with results from other international literature studies. On the contrary, the average boarding rate (*BT*/pax) of 1.34 sec/pax was found to be similar to the overall average boarding rates observed by other researchers but had the largest observed range of data from 0.50 to 3.00 sec/pax. (4.5.5)

- The results of pedestrian microscopic modelling work undertaken by the author has shown that turnstile/access gate demand needs to be lower than turnstile/access gate capacity to achieve acceptable levels of queuing service. The preliminary research presented in this study revealed that turnstile/access gate demand needs to satisfy a volume/capacity (*v*/*c*) ratio of between 0.74 and 0.80 to achieve a reasonable level-of-service of LOS C. It needs to be stressed that this a preliminary finding only as this aspect has not been researched in any depth. For example, the sensitivity of the selected measurement area dimensions upstream of the turnstiles on the results of the relationship has not been investigated. (5.3.6)

- The results of the application of the SP-model for assessing the spatial requirements for the new Century City station was found through ARIMA statistical modelling to adequately represent the VISSIM microsimulation results for the predicted 2015 and 2025 pedestrian volumes. (6.3.4 & 6.3.5)

- The SP-model results for assessing the spatial requirements for the new Langa station was found through ARIMA statistical modelling, to closely match the VISSIM microsimulation results for the predicted 2015 and 2025 pedestrian volumes. (6.4.4 & 6.4.5)

- For both case study stations, the SP-model gave marginally more pessimistic LOS density values for the foyer and concourse infrastructure types when compared to the micromodel results, but this is attributable to the effect of ignoring turnstile delay in the current version of the SP-model. This difference however creates a slightly more conservative design and can therefore be considered acceptable in view of the primary objective of the SP-model as a first-order spatial assessment tool. (6.3.5 & 6.4.5)

7.2 Critical Limitations of the Research

In this section, the validity of the research findings are discussed including the limitations of the research. Potential pitfalls that other researchers may want to avoid or address, should further local research in this direction be attempted, are also discussed.

In relation to this study, the research on pedestrian behaviour within railway station environments would have benefited from further empirical observations to provide a more comprehensive knowledge base of the macroscopic fundamental diagram. Ideally this would have been carried out at different stations and at other geographic locations throughout South Africa. This was not possible within the research period due to a lack of resources.

As indicate in Chapter 6, whilst the calibration of the SP-model incorporated the results of the empirical data collected, the functional assessment of the model incorporated the evaluation of the SP-model results against the results of microscopic modelling conducted through two case study applications. The comparison of the SP-model against real-time observations would have offered a better validation process, but this was not possible due to the significant resource requirements to undertake such surveys. Such a survey would require resources to monitor boarding and alighting passengers at every coach door (up to 50 doors) as well as additional resources located throughout the station monitoring pedestrian flows on the same clock time as the entire survey team. A system of strategically located video cameras could be erected throughout the station to aid in such a data collection process.

A further difficulty encountered during the video recording process was the suitability of camera placement. Ideally, the camera placement and viewpoint of the measurement area would be from directly above to minimise pedestrian tracking errors. To reduce the video angle and error, measurement areas were located as close beneath the camera as possible without compromising the viewable measurement area size in the camera’s view frame.

In this study, no research was conducted on escalators as such infrastructure is not encouraged in South African stations due to the maintenance requirements. Research was also not conducted on ramps which usually occur either in conjunction with stairs or on their own. The research would have benefited in obtaining an empirical database of pedestrian walking behaviour for specific application on ramps. Where ramps and stairs are both provided, or escalators with stairs, such additional research could also identify route choice behaviour between the two infrastructure types.

In this study, only pedestrian flow characteristics during the normal peak hours of operation were observed. Whilst evacuation aspects are considered in the SP-model, the default parameters associated with such an event are still based on capacities suggested by the relevant guidelines obtained from international literature. As observed with the macroscopic flow relationships, the evacuation capacities are likely to be unique to the population demographic and geographic location which has not been considered.

Finally, the SP-model, due to its simplicity, has a narrow range of application. The SP-model cannot be applied to complex station layouts or incorporate large volumes of transferring rail-to-rail passengers. The model currently can only be applied to concourse (either above- or below-ground) type railway stations connected to skywalks that provide public access to either side of the railway station. The model does provide some flexibility of input for variations within this infrastructure layout, but cannot be applied to railway designs that do not conform to this basic generic layout. Whilst this is a genuine limitation, the bulk of new station designs in South Africa conform to this format which is a generic layout that has been endorsed by the rail authority for future suburban line stations in South Africa.

7.3 Data Collection and Capture Problems

This subsection summarises some of the problems that were required to be overcome during the data collection exercise.

Firstly, the approvals processes with regard to station access needed to be honoured. The approvals process proved to be a lengthy exercise and required formal application, presentation and approval from the rail authority to conduct the pedestrian surveys. A Metrorail site access certificate was eventually granted and a confidentiality agreement was signed with the rail authority after having begun negotiations a year earlier.

In terms of survey observational issues, the staircase observations presented the most complications. The initial intention for the staircase observation was to ensure that the bottom flight of steps be captured in the video and the first sets of recordings was setup accordingly.

Once the filming was completed, it emerged after reviewing the footage that the staircase recording angle would be too acute for accurate measurements. This error meant that it would be difficult to determine when a pedestrian would have reached the bottom of the staircase because of the very shallow video angle. It was found that a more perpendicular viewing angle, viz. observing only the top flight of steps would reduce the angle and provide more accurate data capturing information.

In an attempt to test a more perpendicular video angle, a pilot survey was undertaken where it emerged that the limited 3.7 m height of the concourse roof restricted the viewing angle considerably and the full flight of upper steps could not be viewed. A wide-angle lens was subsequently used to address this problem.

Other valuable lessons, observations and comments resulting from the video-survey recording exercise are listed below:

- Since video camera equipment was located outdoors on the open concourse roof, it was vulnerable to the wind and had to be weighed down.

- Occasionally, at the start of the survey, it was found that the video tapes had not been rewound, thus recording only a few minutes worth of data.

- During the calibration process, it was difficult to see the top of the calibration stick in front of the assistant's safety reflector jacket.

- The camera location could unfortunately not be covertly placed, especially for the skywalk surveys; although camera placement was less apparent for the platform and stair surveys.

- Video camera hardware faults occasionally occurred e.g. camera failed to start recording, video tape mechanism faulty, recording head needed cleaning etc.

- The contrast of the sun against a shadow background was a problem especially as the shadows crept over the observation area during the course of the one-hour recording process.

- At Bonteheuwel Station, the skywalk width was wider than the available camera angle so the measurement area was placed in the centre of the walkway. Whilst initially not considered ideal, this turned out to be beneficial since it excluded person/s waiting or leaning against the walls.

- Since the manual data capture process was manually very time intensive, obtaining resources to undertake the data capture and the motivation to continue with this tedious task was difficult.

- Enumerators occasionally struggled to identify gender in certain instances.

- Occasionally, pedestrians would not traverse the entire measurement area (i.e. enter and exit) but loiter or wait/sit within the measurement area. These persons were then tagged as "*markers*" which, although considered when calculating person densities, was excluded from the assessment sample.

- Pedestrians on the stairs would occasionally lean over the railing, which resulted in the target head frame briefly projecting outside the measurement area. This had to be manually corrected afterwards.

- On platforms, three types of persons were observed, viz. those arriving on the platform waiting for trains, those boarding trains during the train dwell and those alighting trains. Each of these person types were tagged as "*Wait*", "*Board*" and "*Alight*" pedestrian types respectively. Only speeds of persons walking through the entire measurement area were considered. The remaining persons, not doing so, were tracked, but tagged as "*markers*".

- It was found that the identification of the "*group size*" attribute was also difficult in dense situations.

- During the boarding and alighting (B&A) surveys, it was occasionally observed that the doors would not open and passengers were forced to open and keep the door physically open themselves. These factors were considered in the eventual data analysis.

7.4 Conclusions

The major findings and conclusions derived from this research are presented in terms of the stated research objectives defined in Section 1.4.

Objective 1: To gain a clear idea and understanding of the current local industry design processes and uses of circulation analysis within station design.

The literature review revealed that the standard procedure for determining the space required for pedestrian areas in railway station building facilities in South Africa uses only basic macroscopic principles. It was discovered that local architects and professionals are using only limited quantified circulation assessments and rely on experience and general architectural standards with reference to minimum regulatory standards such as the SABS 0400, the National Building Regulations document and an out-dated NGS document.

It was discovered that neither of these guideline documents proposed any prescribed spatial assessment methods and therefore opened the way to varied ambiguous assessment techniques by practitioners making the review process particularly complicated and lengthy. The current design process problem was also described as being a "*hit and miss*" affair, resulting in high levels of uncertainty as to whether the spatial facilities provided will actually cater to the demand.

In addition to the clear lack of design guidance, it was observed that the design of spatial requirements using the 30-minute aggregated flow rate (typically used for design purposes in South Africa) did not account for the "*micro-peaking*" effects occurring within this time-frame. In certain instances, these effects were observed to be significant at almost twice the average 30-minute flow rate, thus severely under sizing pedestrian infrastructure for the duration of the "*micro-peaking*".

Without adequate knowledge, it was concluded that it is not sufficient to simply make a number of assumptions and proceed according to "*generic*" design guidance, trusting that it is appropriate to the situation at hand. Through this research programme, and through presentation of several local and international conference papers on the subject, it is demonstrated that the engineering industry should gain a better appreciation and understanding of the field of circulation design and should acknowledge the risks associated with not incorporating quantified assessments of pedestrian movement particularly within railway station environments.

Objective 2: To undertake a comprehensive literature review of the base theory and relevant design processes and the identification of gaps in this knowledge.

The comprehensive literature research conducted in Chapter 2 revealed an understanding of how pedestrians behave at a microscopic level, and how their behaviour is shaped by the various personal, situational, and environmental factors that characterise their interactions with urban spaces and that research in this field is lacking in South Africa.

The literature review revealed that the relationship between pedestrian flow, speed and density is similar to that for vehicle flow parameters, i.e. where the pedestrian flow increases with increasing density, and then decreases rapidly after the density exceeds a critical value and speed maintains a downward trend with increasing density. An interesting finding in the literature review was the argument made by a researcher in the 1970's and confirmed as recently as 2008 that it was a rare occurrence in practice that reducing flow occurs after the optimum flow has been reached despite a multitude of researchers publishing results to the contrary.

In this study, it was shown how much international work has gone into the development of the fundamental macroscopic relationships but that despite the development of fundamental curves for various situations and environments, there is still no consensus regarding the origin of the discrepancies between different fundamental diagrams and the explanation thereof. Through the research conducted in this study, it is shown that demographics and cultural influences on walking behaviour could be contributing to the differences observed in the various fundamental diagrams.

Notwithstanding the lack of local pedestrian behavioural data, the literature review also revealed that pedestrian behaviour in general is not yet fully covered by existing theories, which includes many basic interpretations of pedestrian walking behaviour. Some of the knowledge gaps found included the influence of bi-directional flows on flow rates and walking speeds and the cultural influences on the fundamental relationship between speed, flow and density.

Conducting real-world observations at operational stations in order to increase this understanding of pedestrian behaviour for different infrastructure types in South Africa and developing these relationships towards addressing the local knowledge gap is original. Whilst considerable resources and effort have been applied to the collection, tracking and analysis of pedestrian data from video footage, this is not original and has been applied successfully by other researchers worldwide.

Objective 3: To undertake experimental research on pedestrian behaviour to address these gaps and gain insight into the relation between variables and dependent or response variables describing the process.

In this research, the movement trajectories of 24,410 pedestrians were successfully investigated in a video-based observational study of three infrastructure environments incorporating platforms, stairs and skywalks at Maitland and Bonteheuwel stations in Cape Town, South Africa. Boarding and alighting rates of 7,426 passengers were also observed at these stations. Pedestrian attributes observed for the stair and skywalk datasets included gender, time of day and location. For the platform dataset, gender, body size, encumbrances, group size, time of day and location attributes were captured.

Boarding and alighting behaviour was painstakingly observed by time-stamping all pedestrians passing through coach door openings via the review of the recorded video footage. The time-stamping approach permitted for accurate representation of boarding and alighting behaviour and rates that enabled comparisons to be made against similar observations made in other countries.

Tracking pedestrians was successfully conducted via the use of an in-house developed "*video annotator*" software tool, which allowed for the semi-automatic trajectory tracking and recording of each individual pedestrian. As a result of this comprehensive dataset, both the behaviour of the individual pedestrian (microscopic) and the behaviour of overall pedestrian flows (macroscopic) could be analysed. In particular, the dataset permitted the fundamental relationships between the macroscopic density, composition of the flow (with regard to the walking direction of the pedestrians) and individual space mean speed to be developed and compared against other MFD relationships published.

Objective 4: To compare the macroscopic results of the pedestrian data to other countries and cultures.

On the basis of the empirical research presented in this study, the research results and findings make a number of significant advances in the understanding of pedestrian behaviour within the local railway station environment. The findings, listed in Section 7.1 and discussed in detail in Chapter 4, confirmed the uniqueness of pedestrian behaviour when compared to data from other countries likely to be attributable to the local culture and demographics. As a result, an important conclusion made by the study is that pedestrian flow characteristics are site and region specific and that planners and engineers should take the local pedestrian flow characteristics into account when planning for pedestrian facilities.

The data analysis further showed that pedestrian walking speeds are dependent on the personal characteristics of pedestrians and infrastructure type. Also, it was found that different bi-directional flow ratios significantly impacted capacity flow rates but not speed. It was found that the more unbalanced the flow rate, the greater the impact on capacity. Whilst this fundamental observation was common to all research reviewed in the literature, the impacts of flow ratio on capacity and speed observed in this study was found to be less significant than the results found in other literature.

In conclusion, the results of the new empirical data gathered in this research incorporating boarding and alighting behaviour, MFD relationships, impact of bi-directional flows and coach door capacities is presented in a manner that would be of use by the local engineering and architectural industry.

Objective 5: To develop a prototypical mesoscopic spreadsheet SP-model.

The development of a spreadsheet-based SP-model to assist practitioners to size station infrastructure formed the major objective of this research. In order for the model to be widely accessible and used, the model was built on a Microsoft Excel platform, with simple and intuitive user interfaces. In order for users not to tamper with the worksheet functions, the worksheets are all password protected and access to the macro algorithms has also been restricted.

The SP-model is an advancement of an earlier SP-matrix spreadsheet, (also developed by the author) that was successfully applied by various engineering consultancies in 2007/2008 to test the design parameters of several stations in South Africa. The SP-matrix was however based on the erroneous macroscopic means of calculating station spatial sizing where the "*micro-peaking*" phenomena identified in Objective 1 (and discussed in detail in Subsection 2.1.4) was not considered. The output of the original SP-matrix was also static, and without consideration of the "*micro-peaking*" phenomena, could potentially lead to an under-designed facility. The SP-model now considers dynamic flow conditions within the railway station environment incorporating "*micro-peaking*" effects and is capable of producing detailed longitudinal output criteria to aid the practitioner in assessing and/or designing station spatial requirements. The stated objective of the development of a useable SP-model has therefore been adequately addressed. Further improvements to the model, as indicated in Section 5.4, are however possible.

Objective 6: To calibrate the SP-model according to the results of the local empirical data collected at stations.

From the literature review, it was found that few pedestrian models have been calibrated and validated on real data because of the fact that data collection for the purpose of observing the pedestrian dynamic is a particularly difficult, time consuming and expensive exercise. The reality is that if the effects of the variables on any simulation or other modelling outcome has not been tested and validated against real behaviour, then the modelling offered can be considered questionable.

The results of the empirical surveys undertaken in this study formed the primary default parameter functions and/or values used in the calibration of the SP-model. These parameter functions included walking speed histograms for platforms, stairs and other level terrain, boarding and alighting rates and the macroscopic fundamental relationships (MFD) for the three infrastructure types mentioned. The MFD functions are used by the SP-model purely to keep the calculated flow rate values to within the value ranges observed.

Objective 7: To assess the functional accuracy of the SP-model by comparing the longitudinal results to the microscopic (VISSIM) results through the application of case studies and conclude on the accuracy and applicability of the prototype model in practice.

The functional assessment of the SP-model was based on a comparison of the VISSIM microscopic simulation output results undertaken for the Century City and Langa Stations in Cape Town, South Africa. Both stations were considered ideal for the assessment exercise with multiple platforms, an overhead concourse and multiple staircases servicing the platforms. Decision variables for the assessment process included the comparison of infrastructure density and flow rate longitudinal plots over the entire 30-minute assessment period.

From the comparison of the SP-model outputs to the VISSIM microscopic model outputs, the main conclusion drawn in this study is that identifying first–order spatial requirements at concourse railway stations using a simplistic space-time-volume (STV) model turns out to be feasible and offers a valuable contribution and assessment tool for pedestrian modellers and designers of railway stations. The SP-model considers the complexities of "*pulse-like*" arrivals of train pedestrians, which without engaging in time-consuming modelling, has proved to be a complication for designers of such facilities, especially at the conceptual and preliminary design stage.

7.5 Recommendations for Implementation

This section describes how the results of the research can be applied in practice and provides some suggestions for application of the research.

The primary application of this research in practice involves both designers and the design itself. For the designer, the SP-model may serve as an aid during the design process for "*first order designs*" or as a check to evaluate the current LOS of operations for existing infrastructure. The model does this by indicating the amount of spatial infrastructure needed through longitudinal LOS charts and identification of infrastructure inadequacies during evacuation.

The SP-model may be used both at the beginning of the design process or at the final design stage, although the original intention of the model was that it would be applied as a "*first-order*" model during the conceptual design stage of a railway station. Although the case study assessment process revealed that the SP-model output results closely matched those of the microscopic modelling results, it is nevertheless recommended to conduct microscopic modelling to the final designs for confirmation of spatial provisions made in the design. It is not suggested that the development and application of the SP-model has eliminated the need for microscopic modelling, but has merely reduced the iterative design process involved in the conceptual design stages where no means of quantitative assessment was previously available.

With its simple Excel user interface, the SP-model presented in this study has the significant advantage of being able to input data easily and obtain accurate results in a short space of time.

The secondary impact of this research, conveyed through this study and through the submission of numerous conference papers worldwide, is to help change industry thinking in relation to the importance of pedestrian circulation behaviour in the station design process. It has been demonstrated through this process that the complexities of pedestrian behaviour and influences, together with the specific nature of each station, are of significant importance when designing station infrastructure. In particular, it is hoped that through this work, architects, designers and engineers will gain a better appreciation and understanding of the following:

- The limitations within existing pedestrian circulation design guidance (i.e. NGS 1997 guidelines).
- The acknowledgement of the "*LOS-mismatch*" phenomena and the associated danger of selecting inappropriate flow rate LOS criteria for design purposes.
- The realisation that the provision of turnstiles should not be determined merely by turnstile capacity, but at *v/c* ratios of less than unity.
- The realisation that railway station environments operate with "*pulse-like*" pedestrian demand incorporating "*micro-peaking*" and should be designed as such. Accordingly, using pedestrian demand volumes aggregated over 30 or 15-minute periods should be avoided.
- The fact that spatial infrastructure provision and design should account for complex issues related to the specific local environment and the pedestrian population being addressed.
- The impact of bi-directional flows on infrastructure capacities and speeds.
- The dynamic of the boarding and alighting processes.

The fact that there is little station design guidance in South Africa should lead designers to carry out sampling of values at similar venues to ensure their provisions are appropriate to achieve the chosen level of performance. However, current practice is for designers to use the minimal (and largely inappropriate) guidance that exists to justify their designs.

From this research, there is clear evidence why circulation provisions cannot simply be accounted for by the basic guidance calculations contained within existing guideline documentation such as the NGS document. In relation to design guidance, it is recommended that the local guideline documentation be entirely reviewed where the onus is put on the designer to demonstrate that appropriate consideration is being given to the specific issues relevant to their design.

7.6 Summary of Contributions

An extensive literature review has been conducted in this study that has identified the most up to date research on pedestrian walking characteristics and behaviour within local railway stations. The literature study resulted in the identification of knowledge gaps regarding walking speeds, fundamental relationships between speed, flow and density and a lack of such measurements and data specific to the South African situation.

From a scientific point of view, the results of the empirical observations are also relevant to this study, as the knowledge gaps identified were addressed, especially the "*LOS-mismatch*" phenomena and walking speed distribution of pedestrians on various infrastructure types, indicating a range of design speeds. It emerged that there are differing pedestrian characteristics and relationships that need to be taken into account when ensuring appropriate spatial provision for a station infrastructure. Very little of this is addressed within contemporary design guidance or current practice.

Also, the macroscopic fundamental diagram developed in this study is different from those found in other international literature. Findings reported by other researchers, such as the impact of bi-directional flows on capacity and speed also emerge from the observations made in this study, but with differences in the results.

The main result and significance of this research is a calibrated SP-model for assessing spatial requirements, which not only provides longitudinal (time-series) LOS plots for selected station infrastructure, but provides design checks for evacuation purposes as well. For the designer, the SP-model may serve as an aid during the design process and as support to evaluate improvements in current station operational situations. The SP-model may be used at the start of the design process (indicating the amount of infrastructure space needed) to the final design (indicating operational adequacy of the design provided) as well as the identification of potential design shortcomings for evacuation requirements.

This first version of the model was developed to model pedestrian movement in specific overhead concourse layouts only and cannot be applied to more complex station environments. The innovative characteristic of the SP-model is it's simple user interface and limited user input, yet is able to produce accurate results considered suitable for "*first-order*" design purposes. The SP-model was successfully applied to two case study stations in Cape Town, South Africa and the outcomes of the application corroborate the usefulness of the model as a "*first-order*" spatial assessment tool.

7.7 Recommended Further Research

Although this research has contributed towards the collection and documentation of valuable empirical data applicable to pedestrian behaviour within South African railway stations and ultimately the development of the SP-model for the assessment of infrastructure LOS, further research in a number of directions is proposed. The future research proposed in this section addresses a number of topics, such as additional empirical observations, theoretical research and recommendations for improvements to the SP-model as described further below:

<u>Empirical Data:</u>
The identification of design capacities and flow rate phenomena for walking facilities in railway stations could be developed further. Empirical observations conducted in this study only dealt with pedestrian walking behaviour within two railway stations in Cape Town, South Africa. As a result, only a few variables influencing this walking behaviour could be explored. Additional observations are necessary for different locations both within Cape Town and nationally for different demographic compositions of the flow (including aspects such as gender, age, race group, amount of luggage etc.). Also, different types of infrastructure such as enclosed stairs[f], escalators and ramps (or combinations thereof) not observed in this research, are likely to influence pedestrian walking behaviour and might be included as part of future studies. This will lead to a clearer understanding of the diversity of pedestrian flow characteristics depending on different pedestrian compositions, walking facilities, and particular situations.

Furthermore, the boarding and alighting aspect of this study could benefit greatly if the on-board coach occupancies could be determined simultaneously to the recording of boarding and alighting data. The on-board occupancies could not be surveyed in this research due to the lack of resources.

It was outside the scope of this study to validate the results of the microscopic modelling against which the SP-model was tested. This was not done on the understanding that numerous studies on this very topic have already been conducted and therefore the integrity of the microscopic model has been assumed to be acceptable. Accordingly, there may be great benefit in conducting empirical studies that allow for direct comparison of the SP-model (and other pedestrian microscopic models) to real-time behaviour, although such studies would be difficult to conduct and expensive. With the advent of recent cellphone, bluetooth and other video tracking technologies, it is believed that such surveys could become viable in the foreseeable future.

Another subject of interest to the author and proposed for further study is the impact of platform staircase location on the train coach boarding selection. It is hypothesised that economies of scale (in terms of reduced dwell times) can be achieved by staggering the staircase location at sequential railway stations such

[f] In this research, only "*open*" staircases were available for pedestrian use and were observed. The "*open*" staircases allowed pedestrians to observe oncoming trains from the vantage point of the staircases and therefore unnecessarily "*crowd*" the stairs.

that over a series of stations, the staircases are aligned over the entire length of the train rather than aligned at train centres.

One of the assumptions made in the development of the SP-model, is to assume uniform coach loading distributions for all boarding passengers. However, with time constraints, the dynamic of this boarding process is likely to reveal different coach loading patterns. For instance, the closer the time comes to train departure, the more likely a late passenger will board a coach closest to the base of the stairs. Complicating the issue is the occupancy of the coaches of the arriving train, which will also affect the individuals' boarding decision process.

In this study, it was shown that turnstile demand needed to be lower than turnstile capacity to achieve acceptable levels of queuing service. As this aspect was not researched in any depth, further work in this regard should be undertaken.

As observed with the macroscopic flow relationships, the evacuation capacities are likely to be unique to the population demographic and geographic location which has not been considered and so research in this direction would be advantageous to advance the local knowledge.

Theory:

The research conducted in this study has, for the first time in the country, allowed for the development of macroscopic fundamental diagrams (MFD) for the various infrastructure types specifically within concourse railway stations. MFD's are essential in calibrating simulation models and are not restricted to the SP-model, but applicable to all commercial modelling applications.

With respect to the MFD relationships, we have read in Chapter 2 that current models are hardly consistent, due to the fact that relationships have been drawn up for different conditions, which could not be influenced by the researcher. It would be valuable to extend the MFD relationships developed in this study for different conditions on the same types of infrastructure as well as for similar conditions on different types of infrastructure.

Since the empirical data collected included precise co-ordinate tracking, other microscopic behaviour could be observed including the interpersonal spacing and the relationship between walking speed and spacing preferences which could be undertaken as a future exercise. Other observations that could be undertaken with the data would be the pathway selection across the measurement area and how these pathways are affected by different LOS conditions.

Another aspect of pedestrian behaviour showing demand for research is route choice behaviour. Whilst not observed in this study, only limited international studies on route choice behaviour within railway stations have been conducted. In railway station environments where ramps, stairs and/or escalators are available for pedestrians, a route choice study would be a valuable exercise and should be incorporated into a future version of the SP-model as a route choice algorithm.

SP-Model:

The development of the SP-model, as described in Chapter 5, consists of various algorithmic functions. Each of these functions may be improved, and a detailed account of these improvements is listed in Section 5.4. Whilst case studies have been included in the study for assessment of the SP-model by means of comparing the model results against a more sophisticated microscopic model, a comparison of the results of the model against real-time data would be considered ideal and is subject for further research.

A shortcoming of the SP-model outputs is that the longitudinal plots effectively plot the infrastructure density LOS rather than the pedestrian LOS. It would be better to portray the results as a summation of the longitudinal LOS for each pedestrian as they progress through the various infrastructure items in the station. The time duration element then provides a measure of pedestrian QOS rather than infrastructure LOS.

The QOS measure allows for station design for the individual and is considered more appropriate by the author. It would, for example, enable the designer to act on the cumulative time spent in the respective LOS categories for each pedestrian during the extent of the walking journey.

Another experiment that could be performed using the SP-model is the assessment of the sensitivity of the default parameters on output results, e.g. variance of walking speed distributions.

A final note to make is that although differences between the longitudinal output results of the SP-model and the VISSIM model are observed and documented in the study, it does not necessarily imply that the SP-model is any more accurate or inaccurate than the VISSIM model. Ideally, the SP-model results in future should be benchmarked against real-world observations, a thoroughly onerous endeavour but nevertheless subsequent exercise to this research.

This research has nevertheless succeeded in advancing the approach to station design, empirical data, knowledge and methods held within the local engineering industry. However, this is an early step in changing the perceptions in this country towards ensuring fully informed and appropriate performance-based circulation designs.

8. REFERENCES

A3 Transportation Engineers, (2004). *Khayelitsha Rail Extension: Definition of User Requirements, Stations 4 & 4A*. Preliminary Design report carried out in association with Target Projects, Magqwaka Associate Architects, Ngewu & Associates, Brent Samson & Associates and Manong & Associates for SARCC, Report No: SARCC/SMP/CA1219, File No. AM/SMP/4/2/1/5, Cape Town, 1 June 2004.

AlGadhi, S.A.H., Mahmassani, H.S. & Herman, R. (2001). *A Speed-concentration Relation for Bi-directional Crowd Movements*. In M. Schreckenberg & S. Sharma, (eds.), Pedestrian and Evacuation Dynamics, Srpinger, Berlin, pp. 3 - 20.

Al-Masaeid, H.R., Al-Suleiman, T.I. & Nelson, D.C. (1993). *Pedestrian Speed-Flow Relationship for Central Business District Areas in Developing Countries*. In Transportation Research Record (TRB) 1396, National Research Council, Washington D.C., pp. 69 – 74, 1993.

Amato, P.R. (1983). *The Effects of Urbanization on Interpersonal Behaviour: Field Studies in Papua New Guinea*. Journal of Cross-Cultural Psychology 14, pp. 353 - 367.

American Association of State Highway and Transportation Officials (AASHTO), (1984). *A Policy on Geometric Design of Highways and Streets*. Washington D.C., 1984.

Ando, K., Ota, H. & Oki, T. (1988). *Forecasting the Flow of People*. (In Japanese), Railway Research Review, (45) 8, pp. 8 – 14.

Armitage, P. & Berry, G. (1987). *Statistical Methods in Medical Research*. Redwood Burn Limited, Great Britain.

Arcus Gibb (2008a). *Khayelitsha Station Pedestrian Capacity Analysis Study*. Report conducted for the SARCC, July 2008.

Arcus Gibb (2008b). *Nyanga Station Pedestrian Capacity Analysis Study*. Report conducted for the SARCC, July 2008.

Arcus Gibb (2008c). *Cape Town Station: Pedestrian Capacity Analysis Study.* Report produced for Intersite/SARCC as part of the Revitalisation Project of Cape Town Station, Cape Town, February 2008.

Arup Consulting Engineers, (2008). *Moses Mabhida Preliminary Design Report*. Final Report produced for PRASA/ Ethekweni Municipality, December 2008.

Axhausen, K.W. & Pendyala, R. (2001). *Microsimulation*. Workshop Report of the 8th IATBR Conference, Austin, September 1997.

Bechtel, R. (1970). *Human Movement in Architecture*. In H.M. Proshansky et al (eds.) Environmental Psychology, Rinehart & Winston, New York.

Bennett, S., Felton, A. & Akçelik, R. (2001). *Pedestrian Movement Characteristics at Signalised Intersections*. In 23rd Conference of Australian Institutes of Transport Research, Monash University, Melbourne, Australia, 10 - 12 December 2001.

Berrou, J.L., Beecham, J., Quaglia, P., Kagarlis, M.A. & Gerodimos, A. (2005). *Calibration and Validation of the Legion Simulation Empirical Data*. Pedestrian and Evacuation Dynamics 2005, Springer Berlin Heidelberg, ISBN 978-3-540-47062-5.

Benz, G.P. (1986). *Pedestrian Time-Space Concept, a New Approach to the Planning and Design of Pedestrian Facilities*. Parsons Brinckerhoff Quade & Douglas Inc., 1986.

Bierlaire, M., Antonini, G. & Weber, M. (2003). *Behavioural Dynamics for Pedestrians*. In Proceedings of the 10th International Conference on Travel Behaviour Research, Resource Paper: Session Behavioural Dynamics, Lucerne, August 2003.

Blayney, P.J. (2005). *An Investigation of the Evidence and Effect of Spreadsheet Errors Caused by the Hard Coding of Input Data Values into Formulas*. Faculty of Economics and Business, University of Sydney, pp. 221 – 230.

Blue, J.L. & Adler, V.J. (1999). *Bi-Directional Emergent Fundamental Pedestrian Flows from Cellular Automata Microsimulation*. In Proceedings of the 14th ISTTT, Transportation and Traffic Theory Symposium, Jerusalem, Israel, July 1999.

Blue, J.L. & Adler, V.J. (2000). *Modelling Four-Directional Pedestrian Flow*. Transportation Research Record, 1710 (2000), pp. 20 - 27.

Blue, J.L. & Adler, V.J. (2001). *Flow Capacities from Cellular Automata Modelling of Proportional Splits of Pedestrians by Direction*. In Schreckenberg, M. & Sharma, S. (eds.), Pedestrian and Evacuation Dynamics, Springer, Berlin, pp. 115 -121.

Boles, W. (1981). *The Effects of Density, Sex and Group Size upon Pedestrian Walking Velocity*. Man – Environment Systems, 11, pp. 37 – 40.

Bornstein, M.H. & Bornstein, H.G. (1976). *The Pace of Life*, Nature 259, pp. 557 - 559.

Bornstein, M.H. (1979). *The Pace of Life: Revisited*. International Journal of Psychology 14, pp. 83 – 90.

Bowman, B.L. & Vecellio, R.L. (1994). *Pedestrian Wallking Speeds and Conflicts at Urban Median Locations*. Transportation Research Record, No. 1438, pp. 67 -72.

Box, G.E.P. & Jenkins, G.M. (1976). *Time Series Analysis: Forecasting and Control*. Revised edition. Holden Day Inc., California.

British Standards Institute (BSI), (2000). *Stairs, ladders and walkways - Part 1: Code of Practice for the Design, Construction and Maintenance of Straight Stairs and Winders*, BS5395, ISBN 0 580 33175X.

Britz, C. (2011). *Integrating Rail Transport with other Transport Modes and Operations*, In Proceedings of the 30th Southern African Transportation Conference (SATC 2011), Pretoria, South Africa, 11 -14 July 2011.

Brocklehurst, D., Bouchlaghem, D., Pitfield, D. & Palmer, G. (2003). *Overview of Design Issues Relating to Racecourse Circulation*. Conference paper presented at the 2nd International Conference on Pedestrian and Evacuation Dynamics, School of Computing and Mathematical Sciences, University of Greenwich, London, SE10 9LS, ISBN No. 1-904521-08-8.

Brocklehurst, D., Bouchlaghem, D., Pitfield, D., Green, M.G. & Still, K. (2004). *Capacity Flows on Stadia Stairs; Potential for Low Flow Rate Systems*. Conference Poster Presentation at the 3rd International Symposium on Human Behaviour in Fire, Ulster, UK.

Brocklehurst, D., Bouchlaghem, D., Pitfield, D., Palmer, G. & Still, K. (2005a). *Crowd Circulation and Stadium Design; Low Flow Rate Systems*. Published within Institution of Civil Engineers (ICE) Structure and Buildings Journal, Thomas Telford Ltd., Thomas Telford House, 1 Heron Quay, London, E14 4JD, UK.

Brocklehurst, D., Bouchlaghem, D., Pitfield, D., Green, M.G. & Still, K. (2005b). *Design and Space Planning for Secondary Schools; Considerations for Circulation Modelling*. Accepted for publication within Instituition of Civil Engineers (ICE) Structure and Buildings Journal, Thomas Telford Ltd, Thomas Telford House, 1 Heron Quay, London, E14 4JD, UK.

Brocklehurst, D. (2005c). *People Flow Modelling – Benefits and Applications within Industry*. Doctoral dissertation, Loughborough University, 2005. Centre for Innovative and Collaborative Engineering (CICE), Department of Civil & Building Engineering, Loughborough University, Loughborough. UK.

Bureau of Public Roads (BPR), (1964). *Traffic Assignment Manual.* Urban Planning Division, U.S. Department of Commerce, Washington D.C., 1964.

Burghout, W. (2005). *Mesoscopic Simulation Models for Short-Term Prediction.* Centre For Traffic Research, Institute of Technology, Linköpings University, PREDIKT Project, October 2005.

Cavoukian, A. (1998). *Video Surveillance: The Privacy Implications.* In IPC Practices, Number 10, September 1998, Ontario, Canada.

Cavoukian, A. (2007). *Guidelines for the Use of Video Surveillance Cameras in Public Places.* Information and Privacy Commissioner of Ontario, Toronto, Canada, September 2007.

Cavoukian, A. (2008). *Privacy and Video Surveillance in Mass Transit Systems: A Special Investigation Report.* Privacy Investigation Report MC07-68, Toronto, Canada, 3 March 2008.

Cape Metropolitan Council (CMC), (1998). *On-Track: Operational Assessment of the Cape Metropolitan Railway System*. Final report produced by the Railink Study team as part of the Moving Ahead Cape Metropolitan Transport Plan, Cape Town, July 1998.

Central Statistic Services. (2001). *Census 2001*. Statistics South Africa, 2001.

Central Statistic Services. (2003). *National Travel Survey (NTS) 2003*. Statistics South Africa, 2003.

Cepolina, E. & Tyler, N. (2005). *Understanding Capacity Drop for Designing Pedestrian Environments*. In Walk 21 - VI "Everyday Walking Culture", The 6th International Conference on Walking in the 21st Century, 22 - 23 Sep 2005, Zurich.

Chartered Institute of Building Services Engineers, (CIBSE). (2008). *CIBSE Guide D; Transportation Systems in Buildings*. ISBN-13 : 978-1-903287-61-3, London.

Chatfield, C. (1996). *The Analysis of Time Series: An Introduction*. Fifth edition, St Edmundsbury Press Ltd., Suffolk.

Cheung, C.Y. & Lam, W.H.K. (1997). *A Study of the Bi-directional Pedestrian Flow Characteristics in Hong Kong Mass Transit Railway Stations*. Journal of the Eastern Asia Society for Transportation Studies, Vol. 2, 1997, pp. 1607 – 1620.

Cheung, C.Y. & Lam, W.H.K. (1998). *Pedestrian Route Choices between Escalator and Stairway in MTR Stations*. Journal of Transportation Engineering, Vol. 124, No. 3, Paper No. 15119, May/June 1998, pp. 277 – 285.

City of Cape Town (COCT), (2004). *Summary of 2004/5 Current Public Transport Record*. Produced by the City of Cape Town, Transport, Roads and Stormwater Branch, Cape Town, 2004/5.

Coffin, A.M. (1993). *The Walking Speeds of Elderly Pedestrians*. Masters dissertation, University of Calgary, Canada. Faculty of Civil Engineering, ISBN 97-803-1583-1216, Canada.

Coffin, A.M. & Morrall, J. (1995). *Walking Speeds of Elderly Pedestrians at Crosswalks*. Transportation Research Record, No. 1487, pp. 63 - 67.

Colclough, J.G. & Owens, E. (2009). *Modelling Pedestrian Accessibility using GIS Techniques to Assess Development Sustainability.* In 2009 ETC Proceedings, Planning for Sustainable Land Use and Impact, Session No. 8.

Correia, A.R. & Wirasinghe, S.C. (2006). *Development of a Level-of-Service Standard for Airport Facilities: Application to São Paulo International Airport.* Journal of Air Transport Management (2006), doi:10,1016/j.jairtraman.2006.10.002.

Coutts, J., Lockett, D. & Edwards, N. (2005). *Steps to Safer Stairs*. Canadian Institute of Health Research, Community Health Unit, University of Ottawa, Canada.

CROW (1998). *ASVV: Recommendations for Traffic Provisions in Built-up Areas.* Report 15, CROW.

Cunningham, D.A., Rechnitzer, P.A. & Donner, A.P. (1986). *Exercise Training and the Speed of Self-Selected Walking Pace of Men at Retirement*. Canadian Journal on Ageing 5(1), pp. 19 – 26.

Daamen, W. (2002). *A Quantitative Assessment on the Design of a Railway Station*. In Allen, J, R.J. Hill, C.A. Brebbia, G. Sciutto and S. Sone (Eds.), Computers in Railways VIII (Congress Proceedings of CompRail 2002), Lemnos, Greece, June 2002 (pp. 191 – 200), Southampton: WIT Press.

Daamen, W. & Hoogendoorn, S.P. (2003a). *Research on Pedestrian Traffic Flow in the Netherlands*. In Proceedings Walk 21 IV Walk conference (pp. 101 – 117), Portland, Oregon, United States.

Daamen, W. & Hoogendoorn, S.P. (2003b). *Controlled Experiments to Derive Walking Behaviour*. European Journal of Transport and Infrastructure Research 3 (1), pp. 39-59.

Daamen, W. & Hoogendoorn, S.P. (2003c). *Experimental Research of Pedestrian Walking Behaviour*. In Transportation Research Board Annual meeting 2003, pp. 1 – 16, Washington D.C., National Academy Press.

Daamen, W. & Hoogendoorn, S.P. (2003d). *Qualitative Results from Pedestrian Laboratory Experiments*. In E.R. Galea (Ed.), Pedestrian and evacuation dynamics 2003 (pp. 121 -132). London: CMS Press.

Daamen, W. (2004). *Modelling Passenger Flows in Public Transport Facilities*. Doctoral dissertation, Delft University of Technology, 1998 to 2004. Faculty of Civil Engineering and Geosciences, Department Transport & Planning, Delft University Press, ISBN 90-407-2521-7, The Netherlands.

Daamen, W. & Hoogendoorn, S.P. (2004). *Pedestrian Traffic Flow Operations on a Platform: Observations and Comparison with Simulation Toll Simped*. In Allen, J., Brebbia, C.A., Hill, R.J., Sciutto, G. & Sone, S. (Eds.), Computers in railways IX (Congress Proceedings of CompRail 2004), Dresden, Germany, May 2004 (pp. 125 - 134), Southampton: WIT Press.

Daamen, W., Hoogendoorn, S.P. and Bovy, P.H.L. (2005). *First – order Pedestrian Traffic Flow Theory.* In Transportation Research Board Annual Meeting 2005 (pp. 1-14). Washington D.C., National Academy Press.

Daamen, W., Lee, Y. & Wiggenraad, P. (2008). *Boarding and Alighting Experiments: Overview of Setup and Performance and some Preliminary Results*. Transportation Research Record; Journal of the Transportation Research Board, No. 2042, Transportation Research Board of the National Academies, Washington D.C., 2008, pp. 71 – 81.

Daganzo, C.F. (1994). *The Cell Transmission Model: A Dynamic Representation of Highway Traffic Consistent with the Hydrodynamic Theory*. Transportation Research Part B: Methodological, Volume 28, Issue 4, August 1994, pp. 269 - 287.

Daganzo, C.F. & Geroliminis, N. (2008). *An Analytical Approximation for the Macroscopic Fundamental Diagram of Urban Traffic.* Working Paper, UCB-ITS-VWP-20008-3, UC Berkley Center for Future Urban Transport, April 2008.

Daly, P.N., McGrath, F. & Annesley, T.J. (1991). *Pedestrian Speed/flow Relationships for Underground Stations*. Traffic Engineering and Control, 32, 2, Feb, pp. 76 – 78.

Davis, D.G. & Braaksma, J.P. (1988). *Adjusting for Luggage-Laden Pedestrians in Airport Terminals.* Transportation Research Board Part A, Vol. 22A, No. 5: pp. 375 - 388, 1988.

De Langen, M. & Tembele, R. (2001). *Productive and Liveable Cities: Guidelines for Pedestrian and Bicycle Traffic in African Cities*. Prepared as part of the urban component of the World Bank Sub-Saharan Africa Transport Program. ISBN-10 9058091988.

De Neufville, R. & Grillot, M. (1982). *Designing of Pedestrian Space in Airport Terminals*. In Proceedings of the American Society of Civil Engineers as part of the Transportation Engineering Journal of ASCE, Vol. 108, No. TE1, January 1982.

Department of Transport (DOT), (1994). *Integration of Inter and Intra-City Transport at Points of Mode Transfer*. Report No. RR 93/665, Carried out by the Division of Roads and Transport, CSIR, Pretoria, July 1994.

Department of Transport (DOT), (1997). *Southern African Development Community Road Traffic Signs Manual (SARTSM)*. 3rd Edition, Carried out by De Leuw Cather (North) Pty Ltd., Braamfontein, November, 1997.

Department of Transport (DOT), (2003). *Pedestrian Facility Guidelines: Engineering Manual to Plan and Design Safe Pedestrian and Bicycle Facilities*. Draft 1.0, Carried out by Transportek, CSIR, Pretoria, August 2003.

Dewei, L. & Baoming, H. (2006). *Modelling and Simulation Pedestrian Evacuation Process in Mass Transit Railway Stations*. In proceedings of the 2006 International Symposium on Safety Science and Technology, Changsha, China, 24 – 27 October, 2006.

Federal Highway Administration (FHWA), (1988). *Manual on Uniform Traffic Control Devices*. US Department of Transportation.

Fadin, G., Biasoli, F. & Colmano, L. (1997). *Passengers Automatic Counting System.* In Proceedings of the World Congress on Railway Research, Florence, Italy.

Fernández, R., Zegers, P., Weber, G., Figueroa, A. & Tyler, N. (2010). *Platform Height, Door Width and Fare Collection on Public Transport Dwell Time: A Laboratory Study*. In Proceedings of the 12th World Conference on Transport Research (WCTR), Lisbon, Portugal, 11 - 15 July 2010.

Finnis, K.K. & Walton, D. (2007). *Field Observations of Factors Influencing Walking Speeds*. Paper presented at the 2nd International Conference on Sustainability Engineering and Science, 20 – 23 February 2007.

Fruin, J.J. (1971a). *Pedestrian Planning and Design*. Metropolitan Association of Urban Designers and Environmental Planners, New York.

Fruin, J.J. (1971b). *Design for Pedestrians: A Level-of-Service Concept*. Highway Research Board 355: pp. 1 – 15, 1971.

Fruin, J.J. (1987). *Pedestrian Planning and Design*. Elevator World Inc. (Educational Services Division), Alabama, LIB.CON 70-159312.

Fugger, T.F., Randles, B.C., Stein, A.C., Whiting, W.C. & Gallagher, B. (2000). *Analysis of Pedestrian Gait and Perception-Reaction at Signal-Controlled Crosswalk Intersections*. In Transportation Research Record 1705, Washington D.C., TRB, National Research Council, pp. 20 – 25.

Fujiyama, T. & Tyler, N. (2004). *An Explicit Study on Walking Speeds of Pedestrians on Stairs*. Centre for Transport Studies, University College London, United Kingdom.

Galea, E.R., Blake, S.J. & Dixon, A. (2004). *An Analysis of Passenger Performance on Stairs and Upper Deck Slides during Evacuation Trial: A Report from the VERRES Project*. In Proceedings of the 4th Aircraft Fire and Cabin Safety Research conference, Lisbon, Portugal, 15- 18 November 2004.

Galea, E.R., Hulse, L., Day, R., Siddiqui, A, Sharp, G., Shields, J., Boyce, K. Summerfield, L. Canter, D., Marselle, M. & Greenall, P.V. (2008). *The UK WTC9/11 Evacuation Study: An Overview of the Methodologies Employed and Some Preliminary Analysis*. In Proceedings of the 4th Pedestrian and Evacuation Dynamics (PED) Conference, 27 – 29 February 2008, University of Wuppertal, Germany.

Garrett, B., Annunziato, M., Pannicelli, A. & Liberto, C. (2006). *Modelling Crowd Motion using Swarm Heuristics and Predictive Agents*. In Proceedings of the Nature Inspired Smart Information Systems (NiSIS) 2nd Annual symposium, Puerto de la Cruz, Tenerife, Spain, 29 Nov to 1 Dec 2006.

Gerilla, G.P. (1995). *Proposed Level-of-Service Standards for Walkways in Metro Manila*. Journal of the Eastern Asia Society for Transportation Studies, Vol. 1, No. 3, Autumn, 1995.

Gemzøe, L. (2001). *Are Pedestrians Invisible in the Planning Process? Copenhagen as a Case Study*. In Proceedings of Australia: Walking the 21st Century; An International Walking Conference, 20 to 22 February 2001, Perth, Australia.

Gipps, P.G. & Marksjö, B. (1985). *A Micro-simulation Model for Pedestrian Flows*. Mathematics and Computers in Simulation, Volume 27, Issues 2-3, April 1985, pp. 95 – 105.

Goba (Pty) Ltd., (2009a). *Pedestrian Modelling Assessment: Khayelitsha and Nyanga Stations*. Final report conducted for Arcus Gibb, 6 April 2009.

Goba (Pty) Ltd., (2009b). *Pedestrian Modelling Assessment: Winderemere Station*. Final report conducted for Kwezi V3 Engineers, 23 April 2009.

Goba (Pty) Ltd., (2009c). *Pedestrian Modelling Assessment: Langa Station*. Final Report conducted for Jeffares & Green (Pty) Ltd., 12 June 2009.

Goba (Pty) Ltd., (2009d). *Pedestrian Modelling Assessment: Cape Town Station*. Draft v2 Report conducted for Arcus Gibb/Intersite, 19 June 2009.

Goba (Pty) Ltd., (2009e). *Pedestrian Modelling Assessment: Moses Mabhida Station*. Final Report conducted for Arcus Gibb, September 2009.

Goba (Pty) Ltd., (2010). *Pedestrian Modelling Assessment: Bridge City Station*. Final Report conducted for PRASA, February 2010.

Gupta, A.K. (2005). *A Study on Pedestrian Walking Behaviour*. Masters dissertation, University of Delaware, Faculty of Civil and Environmental Engineering, USA, Summer, 2005.

Gloor, C., Mauron, L. & Nagel, K. (2003). *A Pedestrian Simulation for Hiking in the Alps*. In Proceedings of the 3rd Swiss Transport Research Conference, Session Model & Statistics, Monte Verità / Ascona, March 19 - 21, 2003.

Gonzalez, R.C. & Woods, R.E. (1993). *Digital Image Processing*. Addison Wesley, Reading, MA, U.S.A., 1993.

Government Notice (GN 493A/2003), (2003). *Acts 5/2002, 5/2003; Access to Information and Protection of Privacy Act*. Original Act published and put into operation on 15th March 2002 (GN 116/2002) and amending Act 5/2003 published and put into operation on 10 October 2003.

Hall, F.L. (1997). *Traffic Stream Characteristics*. Revised Monograph on Traffic Flow Theory, www.tfhrc.gov/its/tft/tft.htm, Accessed on 8 January 2009.

Habicht, A.T. & Braaksma, J. P. (1984). *Effective Width of Pedestrian Corridors*. Journal of Transportation Engineering 110, pp. 80 - 93.

Hanisch, A., Tolujew, J., Richter, K. & Schulze, T. (2003). *Online Simulation of Pedestrian Flow in Public Buildings.* In proceedings of the 2003 Winter Simulation Conference, S. Chick. P.J. Sánchez. D. Ferrin and D.J. Morrice (eds.)

Hankin, B.D. & Wright, R.A. (1958). *Passenger Flow in Subways*. In Operational Research Quarterly, Vol. 9 pp. 81 - 88.

Harris, N.G. & Anderson, R.J. (2006). *An International Comparison of Urban Rail Boarding and Alighting Rates*. Institute of Mechanical Engineers, Proc. IMechE, Vol. 221, Part F: Rail and Rapid Transit, DOI:10.1243/09544097JRRT115.

Hofstede, G. (1991). *Cultures and Organizations.* Software of the Mind, McGraw-Hill, London (UK), ISBN 90-254-6913-2.

Helbing, D. (1991). *A Mathematical Model for the Behaviour of Pedestrians*. Behavioural Science 36, pp. 298 – 310.

Helbing, D. (1992). *A Fluid-dynamic Model for the Movement of Pedestrians*. Complex Systems 6, pp. 392 – 415.

Helbing, D., Schweitzer, F., Keltsch, J. & Molnár, P. (1997). *Active Walker Model for the Formation of Human and Animal Trail Systems*. Physical Review E 56, pp. 2527 - 2539.

Helbing, D. & Molnár, P. (1998). *Social Force Model for Pedestrian Dynamics*. Phys. Rev. E, Volume 51, Issue 5, pp. 4282 – 4286.

Helbing, D., Molnár, P., Farkas, I.J. & Bolay, K. (2001a). *Self-organizing Pedestrian Movement*. Environment and Planning B: Planning and Design, Volume 28, pp. 361 – 383.

Helbing, D., Farkas, I.J., Molnár, P. & Vicsek, T. (2001b). *Simulation of Pedestrian Crowds in Normal and Evacuation Situations.* In Pedestrian and Evacuation Dynamics Conference, February 2001.

Helbing, D., Johansson, A. & Al-Abideen, Z. (2007). *The Dynamics of Crowd Disasters: An Empirical Study.* Physical Review E, 75:046109, 2007.

Henderson, L.F. (1971). *The Statistics of Crowd Fluids*. Nature (229), pp. 381 – 383.

Henderson, L.F. & Lyons, D.J. (1972). *Sexual Differences in Human Crowd Emotion*. Nature (240), pp. 353 – 355, 8 December 1972.

Henson, C. (2000). *Levels-of-Service for Pedestrians*. Institute of Transportation Engineers, ITE Journal, Sep 2000, pp. 26 – 30.

Herbst, B.M. & Hunter, K.M. (2008). *Computer Vision.* Undergraduate lecture notes for Computer Science students at the University of Stellenbosch, South Africa, 22 August 2008.

Her Majesty's Railway Inspectorate (HMRI), (1996). *Railway Safety Principles and Guidance: Part 2 Section B: Guidance on Stations.* Health and Safety Executive, HS(G) 153/3, ISBN 0 7176 0713 5.

Her Majesty's Stationery Office (HMSO), (1990). *Guide to Safety at Sports Grounds*. (3rd ed.), Oyez Press Ltd., London.

Her Majesty's Stationery Office (HMSO), (1992). *The Building Regulations 1991 - Approved Document B*, (Section B1, 1992 ed.), HMSO Publications, London, pp. 9 - 40.

Herrmann, W., Hermant, L.F.L. & Emeran, H. (2009). *Pedestrian Modelling in South Africa: A Recent Case Study.* In Proceedings of the 28th Southern African Transportation Conference (SATC 2009), Pretoria, South Africa, July 2009.

Hermant, L. (2009). *Development of a SP-model towards the Macroscopic Assessment of Railway Stations in South Africa*. In Proceedings of the 28th Southern African Transportation Conference (SATC 2009), Pretoria, South Africa, July 2009.

Hermant, L.F.L., Soper, M., Ahuja, S. & Ahuja, R. (2009a). *Applying Innovative VISSIM Microscopic Modelling Techniques for Assessing Railway Station Designs in Cape Town, South Africa.* In Proceedings of the 9th UK PTV VISION User Group Meeting held at Imperial College London, 15 June 2009.

Hermant, L.F.L., Scott, I. & Cronje, P. (2009b). *Taking Pedestrian Microscopic Modelling to the Next Level for Railway Station Design in South Africa*. In the November issue of the SAICE Civil Engineering magazine, November 2009.

Hermant, L.F.L., De Gersigny, M.R. & Ahuja, R. (2010). *Innovative Methods for Assessment of Pedestrian Space Requirements for Railway Stations in South Africa*. In Proceedings of the 12th World Conference on Transport Research (WCTR), Lisbon, Portugal, 11-15 July 2010.

Hermant, L.F.L. & De Gersigny, M.R. (2010). *Microscopic Assessment of Pedestrian Spatial Requirements with Railway Stations in South Africa.* In Proceedings of the 29th Southern African Transportation Conference (SATC 2010), Pretoria, South Africa, August 2010.

Hoel, L.A. (1968). *Pedestrian Travel Rates in Central Business Districts*. In Traffic Engineering (38), pp. 10 – 13.

Hofstede, G. (1991). *Cultures and Organizations: Software of the Mind*. London: McGraw-Hill.

Home Office/Scottish Home and Health Department (1985). *Guide to Safety at Sports Grounds (Football)*, also known as the “Green Guide”, (Third Edition), HMSO, ISBN 0 11 3407610.

Home Office/Scottish Home and Health Department (1998). *Guide to Fire Precuations in Existing Places of Entertainment and Like Premises*, also known as the “Primrose Guide”, HMSO London, ISBN 0 11 3409 079.

Hoogendoorn, S. & Bovy, P.H.L. (2003). *Simulation of Pedestrian Flows by Optimal Control and Differential Games*. Optimal Control Applications and Methods, 2003, 24: pp. 153-172, DOI: 10/1002/oca. 727.

Hoogendoorn, S. P., Daamen, W. & Bovy, P.H.L. (2003). *Extracting Microscopic Pedestrian Characteristics from Video Data*. Paper presented at the Transportation Research Board (TRB) Annual Meeting, Washington, DC.

Hoogendoorn, S.P., Bovy, P.H.L. & Daamen, W. (2004). *Walking Infrastructure Design Assessment by Continuous Space Dynamic Assignment Modelling*. Journal of Advanced Transportation, Volume 38, Issue No. 1, pp. 69 – 92.

Hoogendoorn, S. P. & Daamen, W. (2006). *Microscopic Parameter Identification of Pedestrian Models and Implications for Pedestrian Flow Modelling*. Transportation Research Record, Journal of the Transportation Research Board, No. 1982, Transportation Research Board of the National Academies, Washington D.C., 2006, pp. 57 – 64.

Hoogendoorn, S. P., Daamen, W., de Boer, A. & Vaatstra, I. (2007). *Assessing Passenger Comfort and Capacity Bottlenecks in Dutch Train Stations*. Transportation Research Record, Journal of the Transportation Research Board, No. 2002, Transportation Research Board of the National Academies, Washington D.C., 2007, pp. 107 – 116.

Hostikka, S., Tuomas, P., Tuomo, R., Juha-Matti, S. & Timo, K. (2007). *Evacuation Experiments in Offices and Public Buildings*. VTT Working Paper 85, VTT Technical Research Centre of Finland, Finland.

Hulbert, S. (1976). *Driver and Pedestrian Characteristics*. Transportation and Traffic Engineering Handbook, Edited by J.E. Baerwald, Institute of Traffic Engineers, Englewood Cliffs, Prentice-Hall Inc., New Jersey, pp. 38 - 72.

Illiso Consulting *et al.* (2007). *Kings Park Station: Proposed Commuter Station. Station Location and Environs Investigation*. Draft Report produced for SARCC/Metrorail, February 2007.

Imms, F.J. & Edholm, O.G. (1981). *Studies of Gait and Mobility in the Elderly*. Age and Ageing 10, pp. 147 – 156.

Institute of Transportation Engineers (ITE), (1969). *Transportation and Traffic Engineering Handbook*. Prentice Hall Inc., New Jersey.

Institute of Traffic Engineers (ITE), Technical Council Committee 5-R, (1976). *Characteristics and Service Requirements of Pedestrians and Pedestrian Facilities*. Traffic Engineering, May 1976.

International Maritime Organisation (IMO), (2002). *Interim Guidelines For Evacuation Analysis For New and Existing Passenger Ships*. MSC/Circ. 1033, London, June 2002.

Itami, R.M. (2002). *Estimating Capacities for Pedestrian Walkways and Viewing Platforms*. A Report to Parks Victoria by Geodimensions (Pty) Ltd., 22 Dunstan Avenue, Brunswick, Victoria, Australia, June 2002.

ITS Engineers (Pty) Ltd. (ITS), (2008). *New Winderemere Station: Expected Passenger Volumes Boarding and Alighting at the Station*. A Report conducted for Kwezi V3 Engineers, Cape Town, 6 May 2008.

Jeffares & Green (Pty) Ltd., (J&G), (2007a). *Review of Langa Station Accommodation Requirements and Comparison with Khayelitsha Station 4 and Phillipi Station*. Interim Paper prepared and distributed for project purposes, Cape Town, 1 October 2007.

Jeffares & Green (Pty) Ltd., (J&G), (2007b). *Review of Spatial Parameters Matrices (From Revision 03 to Revision 05)*. Interim Paper prepared and distributed for project purposes, Cape Town, 8 October 2007.

Jeffares & Green (Pty) Ltd., (J&G), (2008). *Transportation Report: Upgrade of Athlone, Heideveld and Langa Train Stations*. Report Stage/Appraisal and Definition, Report prepared for the South African Rail Commuter Corporation Ltd., Intersite Property Management Services and Metrorail, January 2008.

Johnson, B.M. (1977). *Movement of Crowds at Montreal Olympic Park*. In Proceedings of the Seminar/Workshop on Planning, Design and Implementation of Bicycles and Pedestrian Facilities, Palo Alto, 6 – 8 July 1977, pp. 425 – 433.

Johnson, B.M. (1979). *Accessible Pedestrian Systems for those with Physical Disabilities*. Building Practice Note, Division of Building Research, National Research Council of Canada, Ottawa, December 1979.

Jonker and Barnes Architects (J&B), (2007). *Urban Review Report; Upgrade of Athlone, Heideveld and Langa Train Stations*. Report produced for the South African Rail Commuter Corporation Ltd., Intersite Property Management Services and Metrorail, 2007.

Jordaan, P.W. (1981). *Spoorwegingenieurswese vir Voorgraadse Studente*. NVK Leerstoel in Vervoeringenieurswese, Universiteit van Pretoria. (In Afrikaans).

Jordaan, P.W. & Joubert, H.S. (1983). *Optimisering van Padvoertuig-branstofverbruik in Stedelike Gebiede*. Co-operative Scientific Programmes, South Africa. (In Afrikaans).

Kamino, K. (1980). *Human Behaviour and Spatial Design*. The Wheel Extended, A Toyota Quarterly Review, Dai Nippon Printing Co. Ltd.,Vol. 19, No. 3.

Kaup, D.J., Clarke, T.L., Oleson, R. & Malone, L.C. (2007). *Crowd Dynamics Simulation Research*. In Proceedings of the 16th Conference on Behaviour Representation in Modelling and Simulation, Norfolk, 26 – 29 March 2007.

Keßel, A., Klüpfel, H., Wahle, J. & Schreckenberg, M. (2002). *Microscopic Simulation of Pedestrian Crowd Motion*. In Pedestrian and Evacuation Dynamics, M. Schreckenberg and S. Deo Sarma, Eds. (Springer-Verlag), Berlin, pp. 193 - 202.

Kerridge, J., Keller, S., Chamberlain, T. & Sumpter, N. (2004). *Collecting, Processing and Calculating Pedestrian Flow Data in Real-time*. Paper number 05-0191, Transportation Research Board. Annual Meeting, Washington 2005.

Khisty, C.J. (1994). *Evaluation of Pedestrian Facilities: Beyond the Level-of-Service Concept*. In Transportation Research Record 1438, Transportation Research Board, 1994.

Kleijnen, J.P.C. (1992). *Verification and Validation of Simulation Models*. Report 320.92.177, Tilburg University.

Klüpfel, H., Meyer-Köning, T. & Schreckenberg, M. (2002). *Comparison of an Evacuation Exercise in a Primary School to Simulation Results*. Technical report, University Duisburg Essen, Paper submitted to the Fire Safety Journal, 3 April 2002.

Klüpfel, H., Schreckenberg, M. & Meyer-Köning, T. (2003). *Models for Crowd Movement and Egress Simulation*. Traffic and Granular Flow ’03, Berlin, Springer: pp. 357 – 372.

Knoblauch, R.L., Pietrucha, M.T. & Nitzburg, M. (1996). *Field Studies of Pedestrian Walking Speed and Start-Up Time*. In Transportation Research Record 1538, Washington D.C.,TRB, National Research Council, pp. 27-38

Knoflacher, H. (1987). *Verkehrsplanung für den Menschen. Band 1: Grundstrukturen*. Wirtschaftsverlag Orac, Vienna, (In German).

Knoflacher, H. (1995). *Fuβgeher und Fahrradverkehr: Planungsprinzipien*. Boehlau Verlag, Vienna, (In German).

Knutton, M. (2004). *Legion Stands Out in the Crowd.* International Railway Journal, June 2004; 44, 6; ABI/INFORM Trade & Industry, pp. 28 - 29.

Kockelman, K. (2000). *Modelling Traffic’s Flow-Density Relation: Accommodation of Multiple Flow Regimes and Traveler Types.* Transportation 24 (4): pp. 363 - 374, 29 January 2001.

Koushki, P.M. (1988). *Walking Characteristics in Central Riyadh, Saudi Arabia*. Journal of Transportation Engineering, 114 (6), pp. 735 – 744.

Kretz, T., Grunebohm, A., Kessel, A., Klüpfel, H., Meyer-Köning, T. and Schreckenberg, M. (2008). *Upstairs Walking Speed Distributions on a Long Stairway.* Safety Science 46 (2008) pp. 72 - 78, 2008.

Kruger, H.S., Puoane, T., Senekal, M. & van der Merwe, M. (2005). *Obesity in South Africa: Challenges for Government and Health Professionals.* Public Health Nutrition: 8(5), DOI: 10.1079/PHN2005785, 2 June 2005, pp.491 - 500.

Ladetto, Q., Gabaglio, V., Merminod, B., Terries, P. & Schutz, Y. (2000). *Human Walking Analysis assisted by DGPS,* In proceedings of GNSS2000, 4th Conference on Global Navigation Satellite Systems, Edinburgh, Scotland.

Lam, H.K., Morrall, J.F. & Ho, H. (1995). *Pedestrian Flow Characteristics in Hong Kong.* Transportation Research Record, 1487, pp. 56 - 62.

Lam, W.H.K. & Cheung, C.Y. (1999). *Pedestrian Travel Time Function for the Hong Kong Underground Stations – Calibration and Validation*. Transactions, HKIE, Vol. 5, 1999, pp. 39 – 45.

Lam, W.H.K. & Cheung, C.Y. (2000). *Pedestrian Speed/Flow Relationships for Walking Facilities in Hong Kong.* In Journal of Transportation Engineering, Volume 126, No. 4, July/August 2000, pp. 343 – 349.

Lam, W.H.K., Lee, J.Y.S. & Cheung, C.Y. (2001). *A Study of the Bi-directional Pedestrian Flow Characteristics at Hong Kong Signalised Crosswalk Facilities.* Transportation, Vol. 29, No. 2. 2001, pp. 169 – 192.

Lam, W.H.K., Lee, J.Y.S., Chan, K.S. & Goh, P.K. (2003). *A Generalised Function for Modelling Bi-directional Flow Effects on Indoor Walkways in Hong Kong.* Transportation Research Board Part A: Policy and Practice, 37, pp. 789 - 810, 2003.

Landis, B.W., Vattikuti, V.R., Ottenberg, R.M., McLeod, D.S. & Guttenplan, M. (2000). *Modelling the Roadside Walking Environment: A Pedestrian Level-of-Service.* Transportation Research Board, Paper No. 01-0511, November 2000.

Laufer, J. (2008). *Passenger and Pedestrian Modelling at Transport Facilities.* Making Connections: People, Places, Goods and Services: Australian Institute of Traffic Planning and Management National Conference, Perth, 3 – 5 September 2008.

Lee, J.Y.S. & Lam, W.H.K. (2003). *Levels-of-Service for Stairway in Hong Kong Underground Stations.* Journal of Transportation Engineering, March/April 2003.

Lee, J.Y.S. & Lam, W.H.K. (2005). *The Variation of Walking Speeds on a Uni-directional Walkway and on a Bi-Directional Stairway.* Transportation Research Board, Annual Meeting.

Lerner, G., Hochstaedter, A., Kates, R., Demir, C., Meier, J. & Poschinger, A. (2000). *The Interplay of Multiple Scales in Traffic Flow: Coupling of Microscopic, Mesoscopic and Macroscopic Simulation.* In Proceedings of the 7th ITS World Congress on Intelligent Transport Systems, Turin, Italy, 2000.

Levine, R. (1997). *A Geography of Time: The Temporal Misadventures of a Social Psychologist, or How Every Culture Keeps Time Just a Little Bit Differently*. New York: Basic Books/Harper Collins.

Lin, Y. & Fuh, C. (1999). *Correcting Distortion for Digital Cameras*. In Proceedings of the National Science Council. ROC (A), Volume 24, No. 2, pp. 115 - 119, 1999.

London Underground Limited (LUL), (2005). *Engineering Standard: Station Planning*. Chief Engineer's Directorate, Number : 2-03001-024, Issue No. A1, April 2005.

Lu, Y.J., Tang, Y.Y., Pirard, P., Hsu, Y.H. & Cheng, H.D. (1990). *Measurement of Pedestrian Flow Data Using Image Analysis Technique*. Transportation Research Record No. 1281, pp. 87 – 96.

Makris, D. & Ellis, T. (2002). *Path Detection in Video Surveillance.* Image and Vision Computing, 20, pp. 895 – 903.

Martinez-Schnell, B. & Zaidi, A. (1989). *Time Series Analysis of Injuries*. Stat Med 8: pp. 1497 - 1508.

Mateo-Babiano, I. (2003). *Sustainable + Mobility + Management: Pedestrian Space Management as a Strategy in Achieving Sustainable Mobility*. Transport Research and Infrastructure Planning Laboratory, Civil Engineering Department, University of Tokyo, Japan.

Matsumoto, M., Miska, M., Kuwahara, M. & Tanaka, S. (2010). *Microscopic Pedestrian Simulation Considering Heterogeneity*. In Proceedings of the 12th World Conference on Transport Research (WCTR), Lisbon, Portugal, 11-15 July 2010.

Matzopoulos, R., Seedat, M., Marais, S. & van Niekerk, A. (2004). *A Profile of Fatal Injuries in South Africa: A Platform for Safety Promotion*. Medical Research Council (MRC) Policy Brief, No. 2, March 2004.

Mauron, L. (2002). *Pedestrian Simulation Models.* Diploma Thesis. ETH Zürich, Swiss Federal Institute of Technology, October 2002.

McCleary, R. & Hay, R.A. (1980). *Applied Time Series Analysis for the Social Sciences*. Sage publications Inc., California.

Metronet (2005). *Generic Fire Strategy*. Report prepared by Atkins, Document no. RPT-FRS-TM050569304, October 2005.

Metrorail (2000). *Access Doors for 5M2A Metro*. Operating and Maintenance Manual, No. E138 763-NT, April 2000.

Milazzo II, J.S., Rouphail, N.M., Hummer, J.E. & Allen, D.P. (1999). *Quality-of-Service for Uninterrupted Pedestrian Facilities in the 2000 Highway Capacity Manual*. Presented at the 78th Annual Meeting of the US Transportation Research Board in Washington D.C., TRB Paper 99-0132, January 1999.

Minderhoud, M., Botma, H. & Bovy, P.H.L. (1997). *Assessment of Roadway Capacity Estimation Methods*. Transportation Research Record, Transportation Research Board, National Research Record Council, Washington D.C.

Montgomery, D. & Runger, G. (2007). *Applied Statistics and Probability for Engineers*. Fourth Edition, United States of America: John Wiley and Sons, 2007.

Morrall, J.F., Ratnayake, L.L. & Seneviratne, P.N. (1991). *Comparison of Central Business District Pedestrian Characteristics in Canada and Sri Lanka.* Transportation Research Record, 1294, pp. 57 – 61.

Mori, M. & Tsukaguchi, H. (1987). *A New Method for Evaluation of Level-of-Service in Pedestrian Facilities.* Transp. Res., 21A(3), pp. 223 - 234, 1987.

Mozer, D. (1994). *Calculating Multi-Modal Levels-of-Service (Abridged).* International Bicycle Fund, 1994, <http://www.ibike.org/lcs.htm>.

Muraleetharan, T. & Hagiwara, T. (2006). *A Study on Evaluation of Pedestrian Level-of-Service along Sidewalks and at Intersections Using Conjoint Analysis.* Division of Urban and Environmental Engineering.

Muramatsu, M., Irie, T. & Nagatani, T. (1999). *Jamming Transition in Pedestrian Counter Flow.* Physica A 267, pp. 487 - 498.

Naderi, J.R. (2003). *On the Nature of Walking and Learning Pedestrian Environments*. Architecture Research Center Consortium, Tempe, Arizona, 2003.

Nagel, K. & Schreckenberg, M. (1992). *A Cellular Automaton Model for Freeway Traffic*. Journal Phys. I France 2 (1992).

Navin, F.P.D. & Wheeler, R.J. (1969). *Pedestrian Flow and Characteristics*. In Traffic Engineering, 39, pp. 30 – 36, June 1969.

National Fire Protection Association (NFPA 130), (1997), *NFPA 130-1997: Standard for Fixed Guideway Transit and Passenger Rail Systems*. 1997 Edition, Quincy, Massachusetts, NFPA, 1997.

National Fire Protection Association (NFPA 101), (2003), *NFPA 101-2003: Life Safety Code*. Quincy, Massachusetts, NFPA, 2003.

National Fire Protection Association (NFPA 130), (2003), *NFPA 130-2003: Standard for Fixed Guideway Transit and Passenger Rail Systems*. 2000 Edition, Quincy, Massachusetts, NFPA, 2003.

New York City: Department of City Planning (NYC DCP), (2006), *New York City Pedestrian Level-of-Service Study: Phase 1*. April 2006.

Nicoll, G. (2007). *Spatial Measures Associated with Stair Use*. In the American Journal of Health Promotion, 10 January 2007, pp. 346 – 352.

Oeding, D. (1963). *Verkehrsbelastung und Dimensionierung von Gehwegen und anderen Anlagen des Fussgangerverkehrs*. Strassenbau und Strassenverkehrstechnik, Heft 22, Bonn. (In German).

O'Flaherty, C.A. & Parkinson, M.H. (1972). *Movement on a City Centre Footway*. In Traffic Engineering and Control, 13, pp. 434 – 438.

Okazaki, S. (1979). *A Study of Pedestrian Movement in Architectural Space, Part 1: Pedestrian Movement by the Application of Magnetic Models*. Trans. of A.I.J., No. 283, pp. 111 - 119.

Okazaki, S. & Matsushita, S. (1993). *A Study of Simulation Model for Pedestrian Movement with Evacuation and Queuing*. Department of Architecture and Civil Engineering, Faculty of Engineering, Fukui University, 3-9-1, Bunkyo, Fukui, Japan.

Older, S.J. (1968). *Movement of Pedestrians on Footways in Shopping Streets*. In Traffic Engineering and Control, August, 10(4), pp. 160 – 163.

Osaragi, T. (2004). *Modelling of Pedestrian Behaviour and its Application to Spatial Evaluation*. In Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems – Volume 2, ISBN: 1-58113-864-4, pp. 836 – 843, New York.

Pachi, A. & Ji, T. (2005). *Frequency and Velocity of People Walking*. The Structural Engineer 83, pp. 36 - 40.

Pauls, J.L. (1980). *Building Evacuation: Research Findings and Recommendations*. In Fires and Human Behaviour (Chapter 14), John Wiley & Sons, Chichester/New York/Brisbane/Toronto.

Pauls, J.L. (1987). *Calculating Evacuation Times for Tall Buildings*. Fire Safety Journal, 12, pp. 213 – 236.

Pauls, J.L. (1995). *Movement of People*. In DiNenno (ed.) SFPE Handbook of Fire Protection Engineering, 2nd edition, pp. 3-263 to 3-285, 1995.

Pauls, J.L. (2004). *Suggestions on Evacuation Models and Research Questions*. In Proceedings of 3rd International Symposium of Human Behaviour in Fire, Belfast, Ulster, UK.

Papacostas, C.S. & Prevedouros, P.D. (1993). *Transportation Engineering and Planning*. 2nd Edition, Prentice-Hall International, New Jersey.

Penn, A. & Turner, A. (2001). *Space Syntax Based Agent Simulation*. In the 1st International Conference on Pedestrian and Evacuation Dynamics, University of Duisburg, Germany, 2001.

Peponis, J. (2004). *Space Syntax*. In Implication Newsletter by Informe Design, Vol. 04, Issue 12. www.informedesign.umn.edu, University of Minnesota.

Peschel, R. (1957). *Untersuchungen uber die Leistangsfahigkeit ungeschutzter Fussgangeruberwege (Research into the Capacity of Unprotected Pedestrian Crossings)*. (in German), Strassertechnik, 5, part 6, pp. 63 – 67.

Pheasant, S. (2002). *Bodyspace – Anthropometry, Ergonomics and the Design of Work.* Taylor and Francis, ISBN 0748403264, ErgoBase from the Biomechanics Corporation of America, Inc. In database of the world population sizes, dimensions and aerobic work from Bodyspace.

Polus, A., Schofer, J.L. & Ushpiz, A. (1983). *Pedestrian Flow and Level-of-Service*. In Journal of Transportation Engineering, Vol. 109, January, pp. 46 – 56.

PTV Traffic Mobility Logistics (2008). *VISSIM 5.10 User Manual*. PTV AG 2008.

Puong, A. (2000). *Dwell Time Model and Analysis for the MBTA Red line.* Accessed from http://www.core.org.cn/NR/rdonlyres, Civil and Environmental Engineering.

Pushkarev, B. & Zupan, J.M. (1975a). *Urban Space for Pedestrians*. MIT Press, Cambridge, Massachusetts.

Pushkarev, B. & Zupan, J.M. (1975b). *Capacity of Walkways*. Transportation Research Record, 538: pp.1 - 15, 1975.

Passenger Rail Agency of South Africa (PRASA), (2009). *Capital Investment Budget 2009/10; Installation of New Technology Passenger Access Gates*. Report authored by P. Cronje for application to the Cape Town Station Upgrade Project, Cape Town, 25 June 2009.

Predtechenskii, V.M. & Milinskii, A.I. (1969). *Planning for Foot Traffic Flows in Buildings*. Stoiizdat Publishers, Moscow, Translated and published by Amerind Publishing Co. Pvt. Ltd., New Delhi.

ProRail Spoorontwikkeling (2005). *Basisstation 2005, Deel A en B, Functionele normen en richtlijnen voor treinstations*. (In Dutch), Document no. 2052802, 26 July 2005.

Rail Safety & Standards Board (2003). *Managing Large Events and Perturbations at Stations: Passenger Flow Modelling Technical Review*. Third Revision, Document No. RS021/R.03, Evergreen House, London, 15 October 2003.

Railway Procurement Agency (RPA), (2006). *Architectural Criteria for Design Standards*. Second Edition, Document ARC.DMr.0001.02, 20 June 2006.

Rindsfüser, G. & Klügl, F. (2007). *Agent-Based Pedestrian Simulation*. *A Case Study of the Bern Railway Station*. In: DISP, 43 (2007) 3-170, S. 9 – 18.

Roddin, M. (1981). *A Manual to Determine Benefits of Separating Pedestrians and Vehicles*. Report 240, Transportation Research Board.

Ronald, G. (2008). *Road Rage – A South African Perspective*. Accessed from Arrive Alive website ww.arrivealive.co.za. Automobile Association of South Africa, 17 July 2008.

Ross, J. (2000). *Railway Stations: Planning, Design and Management*. Architectural Press, Linacre House, Jordan Hill, Oxford, UK, ISBN 0 7506 4376 5.

Rouphail, N., Hummer, J., Milazzo, J. & Patrick Allen, D. (1998). *Literature Review for Chapter 13, Pedestrians of the Highway Capacity Manual*. Federal Highway Administration Report, February 1998.

Saif, M.A. (2009). *Pedestrian Characteristics in the Holy City of Makkah and Suitability of the Highway Capacity Manual to Evaluate their Facilities*. Umm Al-Qura University, Journal of Engineering and Architecture, Volume 1, No. 1, pp. 50 – 68, 2009.

Sarkar, S. (1995). *Determination of Service Levels for Pedestrians with European Examples*. In Transportation Research Record 1405, TRB, National Research Council, Washington D.C., 1995, pp. 35 – 42.

Sarkar, A.K. & Janardhan, K.S.V.S. (1997). *A Study on Pedestrian Flow Characteristics*. In CD-ROM with Proceedings, Transportation Research Board, Washington.

Schadschneider, A., Klingsch, W., Klüpfel, H., Kretz, T., Rogsch, C. & Seyfried, A. (2009). *Evacuation Dynamics: Empirical Results, Modelling and Application*. Encyclopaedia of Complexity and System Science, Robert A. Meyers (Ed.), Springer, 2009, ISBN 978-0-387-75888-6, Vol. 3, pp. 3142.

Schaefer, L. (2000). *Flow Theory for Flocks of Autonomous Mobile Physical Agents*. Doctoral dissertation, Arizona State University, USA, August 2000.

Schelhorn, T., O'Sullivan, D., Hakley, M. & Thurstain-Goodwin, M. (1999). *STREETS: An Agent-Based Pedestrian Model*. Centre for Advanced Spatial Analysis, University College London, Working Paper 9, London.

School of Science and Conservation (SCICON), (1972). *Safety in Football Stadia: A Method of Assessment*. Study conducted for the Wheatley enquiry into crowd safety at sports grounds, London.

Seneviratne, P.N. & Morrall, J.F. (1985a). *Analysis of Factors Affecting the Choice of Route of Pedestrians*. Transportation Planning and Technology, Vol. 10, 1985, pp. 147 - 159.

Seneviratne, P.N. & Morrall, J.F. (1985b). *Level-of-Service on Pedestrian Facilities*. Transportation Quarterly, Vol. 39, No, 1, 1985, pp. 109 – 123.

Sleight, R.B. (1972). *The Pedestrian: Human Factors in Highway Traffic Safety Research*. Wiley-Interscience.

Society of Fire Protection Engineers/National Fire Protection Association (SFPE), (1995). *The SFPE Handbook; Fire Protection Engineering*. 2nd Edition.

South African Bureau of Standards (SABS), (1990). *The Application of the National Building Regulations*. First Revision Published by SABS, SABS 0400-1990, Private Bag X191, Pretoria.

South African National Standards (SANS), (2005). *Railway Safety Management, Part 1: General*. SANS 3000-1:2005, Edition 1, RSR 001:2005, Edition1, Pretoria, 2005.

South African Rail Commuter Corporation Ltd. (SARCC), (1997). *Metro Station Acquisition: Norms, Guidelines and Standards*. Prepared by Propenta (Pty) Ltd. Engineering and Project Management and Protekon Architects, October 1997.

South African Rail Commuter Corporation Ltd. (SARCC), (2005). *Review of Commuter Demand*. Working Document on Work Stream 5 of the National Passenger Rail Plan. Produced by SSI Consulting Engineers, February 2005.

South African Rail Commuter Corporation Ltd. (SARCC), (2006a). *The Western Cape Regional Rail Plan*. Second Draft Report, No. J25046, July 2006.

South African Rail Commuter Corporation Ltd. (SARCC), (2006b). *National Railplan: Consolidated Report*. Final Report, August 2006.

South African Rail Commuter Corporation Ltd. (SARCC), Metrorail, City of Cape Town and Provincial Government of the Western Cape. (2008a). *2007 Rail Census Report: Western Cape*. Final Draft Report produced by Asakhe Consulting Engineers, May 2008.

South African Rail Commuter Corporation Ltd. (SARCC), (2008b). *Access Gates for Stations: Technical Specifications (Draft)*. SARCC Doc. No. BIP/12/11/3 version 00, Authored by E. Swanepoel, October 2008.

SPSS (1994). SPSS Trends 6.1, Spss Inc., USA.

Stanbury, J. & Scott, I. (2005). *Towards Improving the Accessibility of Commuter Rail to Special Needs Passengers*. In Proceedings of the 24th Southern African Transport Conference (SATC 2005), Pretoria, July, 2005.

Stonor, T., Beatriz de Arruda Campos, M. & Smith, A. (2003). *Towards a Walkability Index.* In Proceedings of the European Transport Conference (ETC), Strasbourg, France, 2003.

Still, G.K. (2000). *Crowd Dynamics*. Doctoral dissertation, University of Warwick, Department of Mathematics, Warwick, UK, August 2000.

Stucki, P., Gloor, C. & Nagel, K. (2003). *Obstacles in Pedestrian Simulations.* Department of Computer Sciences, ETH Zurich, September 2003.

Surti, V.H. & Burke, T.J. (1971). *Investigation of the Capacity of the Whitehouse Sidewalk for Orderly Demonstrations*. Highway Research Record, No. 355.

Tanaboriboon, Y., Hwa, S.S. & Chor, C.H. (1986). *Pedestrian Characteristics Study in Singapore*. Journal of Transportation Engineering, ASCE, 112(3), pp. 229 - 235.

Tanaboriboon, Y. & Guyano, J.A. (1991). *Analysis of Pedestrian Movements in Bangkok*. Transportation Research Record, 1294, pp. 52 – 56.

Tarawneh, M.S.(2001). *Evaluation of Pedestrian Speed in Jordan with Investigation of some Contributing Factors*. Journal of Safety Research 32, pp. 229 - 236.

Teknomo, K., Takeyama, Y. & Inamura, H. (2000a). *Review on Microscopic Pedestrian Simulation Model*. In Proceedings of the Japan Society of Civil Engineering Conference, Morioka, Japan, March 2000.

Teknomo, K., Takeyama, Y. & Inamura, H. (2000b). *Data Collection Method for Pedestrian Movement Variables*. Published in "Dimensi Tekni Sipil", Volume 2, No. 2, September 2000.

Teknomo, K., Takeyama, Y. & Inamura, H. (2001a). *Tracking System to Automate Data Collection of Microscopic Pedestrian Traffic Flow*. In Proceedings of the 4th Eastern Asia Society for Transportation Studies, Hanoi, Vietnam, Vol. 3 No. 1, pp.11 - 25, October 2001.

Teknomo, K., Takeyama, Y. & Inamura, H. (2001b). *Measuring Microscopic Flow Performance for Pedestrians*. In Proceedings of the 9th World Conference on Transport, Seoul, Korea.

Teknomo, K. (2002). *Microscopic Pedestrian Flow Characteristics: Development of an Image Processing Data Collection and Simulation Model*. Doctoral dissertation, Department of Human Social Information Sciences, Graduate School of Information Sciences, Tohoku University, Japan, March 2002.

Tennenbaum, A.N. & Fink, E.L. (1994). *Temporal Regularities in Homicide: Cycles, Seasons and Autoregression*. J Quant Criminol 10: pp 317 - 342.

Thompson, P. (2004). *Simulex: Simulated People have needs too*. Integrated Environmental Solutions Ltd., 141 St. James Road, Glasgow, G4 0LT, UK, www.iesve.com.

Tolley, R. (2003). *Providing for Pedestrians: Principles and Guidelines for Improving Pedestrian Access to Destinations and Urban Spaces.* Department of Infrastructure, Victoria, Australia, July 2003.

Tolujew, J. (2003). *Prozessbilder als Grundlage für die Prozessanalyse in Materialflusssystemen*. (In German), In Simulation-technik, 17, ASIM Symposium in Magdeburg, R. Hohmann (Hrsg), SCS Int., Ghent 2003, pp. 343 – 348.

Tolujew, J. & Alcalá, F. (2004). *A Mesoscopic Approach to Modelling and Simulation of Pedestrian Traffic Flows*. In Proceedings of 18th European Simulation Multiconference, Graham Horton (c), SCS Europe, ISBN 3-936150-35-4.

Transportation Research Board (TRB), (1985), *Highway Capacity Manual (HCM)*. Transportation Research Board, National Research Council, Washington D.C., 1985.

Transportation Research Board (TRB), (1999a), Transit Capacity and Quality of Service Manual (TCQSM), *Part 1: Introduction and Concepts*. TCRP Web Document 6, Project A-15, Contractor's Final Report, Transit Cooperative Research Program, Transportation Research Board, National Research Council, Washington D.C., January 1999.

Transportation Research Board (TRB), (1999b), Transit Capacity and Quality of Service Manual (TCQSM), *Part 5: Rail Transit Capacity*. TCRP Web Document 6, Project A-15, Contractor's Final Report, Transit Cooperative Research Program, National Research Council, Washington D.C., January 1999.

Transportation Research Board (TRB), (1999c), Transit Capacity and Quality of Service Manual (TCQSM), *Part 7: Stop, Station and Terminal Capacity*. TCRP Web Document 6, Project A-15, Contractor's Final Report, Transit Cooperative Research Program, National Research Council, Washington D.C., January 1999.

Transportation Research Board (TRB), (2000). *Highway Capacity Manual (HCM)*. National Research Council, Washington D.C., 2000.

Tregenza, P.R. (1976). *The Design of Interior Circulation: People and Buildings*. London: Crosby Lockwood.

Trompenaars, F. & Hampden-Turner, C. (1998). *Riding the Waves of Culture – Understanding the Cultural Diversity of Business*. Nicholas Brealey Publishing, London (UK), ISBN 1-85788-176-1.

Trompenaars, F. & Hampden-Turner, C. (2004). *Meeting of the Minds: Gaining Competitive Advantage through Reconciling Cultural Differences*. THT Trompenaars Hampden-Turner, Culture for Business Consulting, Sorento, 5 October 2004.

Turner, F.S.P. (1959). *Preliminary Planning for a new Tube Railway across London*. ICE Proceedings, Volume 12, Issue 1, pp. 19 - 38, February 1959.

University of Stellenbosch (2009). *Framework Policy for the Assurance and Promotion of Ethically Accountable Research at Stellenbosch University.* Dowloaded from www.sun025.sun.ac.za, 20 March 2009.

Verster, B. (2004). *Normative Surveys to Determine End-User Perceptions of Public Transport Interchanges.* In Proceedings of the 23rd Southern African Transport Conference (SATC 2004), ISBN:1-920-01723-2, 12 – 15 July 2004.

Virkler, M.R. & Elayadath, S. (1994). *Pedestrian Speed-Flow-Density Relationships*. Transportation Research Record 1438, TRB, National Research Council, Washington D.C. 1994, pp. 51 – 58.

Virkler, M.R. (1998). *Prediction and Measurement of Travel Time along Pedestrian Routes*. In Transportation Research Record 1636, National Research Council, Washington D.C., pp. 37 – 42.

Van As, S.C. & Joubert, H.S. (1993). *Traffic Flow Theory*. 4th Edition, VIAED, University of Pretoria, Pretoria.

Wang, Z. & Liu, M. (2006). *Simulation of Bi-directional Flow Effects on Indoor Walkway*. In Proceedings of the 2006 International Symposium on Safety Science and Technology, Changsha, China, 24 – 27 October 2006.

Weidmann, U. (1993). *Transporttechnik der Fußgänger*. Report Schriftenreihe Ivt-Berichte 90, ETH Zürich, (In German).

Whyte, W.H. (1988). *City, Rediscovering the Center*. New York: Doubleday, 1988.

Wiggenraad, P.B.L. (2001). *Alighting and Boarding Times of Passengers at Dutch Railway Stations*. Report, TRAIL Research School.

Willis, A., Kukla, R., Kerridge, J. M. & Hine, J. (2002). *Laying the Foundations: the use of Video Footage to Explore Pedestrian Dynamics in PEDFLOW*. In Pedestrian and Evacuation Dynamics (Eds) M. Schreckenberg, S. D. Sharma (Springer, Berlin), pp. 181 – 186.

Willis, A., Kukla, R., Kerridge, J.M., Havard, C. & Gjersoe, N. (2004). *Human Movement Behaviour in Urban Spaces: Implications for the Design and Modelling of Effective Pedestrian Environments*. In Environment and Planning B: Planning and Design 2004, Volume 31, pp. 805 – 828.

Wilson, D.G. & Grayson, G.B. (1980). *Age-related Differences in the Road Crossing Behaviour of Adult Pedestrians*. Report, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.

Xiang, Z., Kok Wai, F. & Hoong Chor, C. (2003). *Pedestrian Speed-Flow Model on Escalators and Staircases in Singapore MRT Stations*. Department of Civil Engineering, National University of Singapore.

Ye, J.H., Chen, X., Yang, C. & Wu, J. (2008). *Walking Behaviour and Pedestrian Flow Characteristics for Different Types of Walking Facilities.* Journal of the Transportation Research Board, No. 2048, Transportation Research Board of the National Academies, Washington D.C., 2008, pp. 43 – 51.

Young, S.B. (1998). *Evaluation of Pedestrian Walking Speeds in Airport Terminals*. Transportation Research Record, 1674, pp. 20 – 26.

Yu, M.F. (1993). *Level-of-Service Design Standards for Non-motorized Transport in Shanghai, China.* AIT Thesis No. GT 93-35, Asian Institute of Technology, Bangkok.

Zacharias, J. (2001). *Pedestrian Behaviour and Perception in Urban Walking Environments.* Journal of Planning Literature, Vol. 16, No. 1, August, 2001.

Zhang, L. (2004). *Signalized Intersection Level-of-Service that Accounts for User Perceptions.* Doctoral dissertation, University of Hawaii, Faculty of Civil and Environmental Engineering, Hawaii, December 2004.

Zhang, Q., Han, B. & Li, D. (2008). *Modelling and Simulation of Passenger Alighting and Boarding Movement in Beijing Metro Stations*. Transportation Research Part C, 16 (2008), pp. 635 – 649.

9. BIBLIOGRAPHY

The list below are publications not specifically referred to (or cited) in the dissertation text, but which contributed to the author's knowledge base.

ACG Architects and Development Planners & KMH Architects, (2008). *Philippi Station Stage 3 Design*. Carried out for Intersite Property Management Services and SARCC, Cape Town, 25 March 2008.

Asakhe Consulting Engineers, (2007). *Philippi Station: Pedestrian Analysis*. First Draft, Cape Town, December 2007.

Asakhe Consulting Engineers, (2008). *2007 Rail Census Report: Western Cape*. Final Draft prepared for Metrorail, City of Cape Town, SARCC and the Western Cape Provincial Government, Cape Town, May 2008.

Brogan, D.C. & Johnson, N.L. (2003). *Realistic Human Walking Paths*. In Proceedings of the 16th International Conference on Computer Animation and Social Agents (CASA 2003). ISBN 0-7695-1934-2.

Burgess, J.W. (1983). *Interpersonal Spacing between surrounding Nearest Neighbours reflects Familiarity and Environmental Density,* Ethology and Sociobiology, Volume 4, pp. 11 - 17.

City of Cape Town (COCT), (1999). *Moving Ahead: Cape Metropolitan Transport Plan, Part 2: Public Transport Strategic Component*. Produced by the City of Cape Town, Transport, Roads and Stormwater Branch, Cape Town, ISBN 0-620-24655-3, September 1999.

City of Cape Town (COCT), (2006). *Rail Framework*. Produced by Asakhe Consulting Engineers for the City of Cape Town, Transport, Roads and Stormwater Branch, Cape Town, 2006.

Corthout, R. & Frederix, R. (2007). *Afwikkeling van Voetgangersstromen in Stationterminals.* (In Dutch), Masters dissertation, Katholieke Universitiet Leuven, Faculteit Toegepaste Wetenschappen, Departement Burgerlijke Bouwkunde, 29 May 2007.

Daamen, W. (2002). *Simped: A Pedestrian Simulation Tool for Large Pedestrian Areas*. Delft University of Technology, Department of Civil Engineering, Delft, Netherlands.

Daamen, W., Hoogendoorn, S.P. & Lundgren, N. (2007). *Passengers Evacuating in Rail Tunnels*. In Proceedings of the 86th TRB Annual Meeting, Washington D.C., USA, 30 March 2007.

De Neufville, R. (1995). *Designing Airport Passenger Buildings for the 21st Century*. Transport Journal. In Proceedings of the Institute of Civil Engineers (UK), Paper 10284.

Department of Transport (DOT), (1985). *Bus Terminals and Bus Stations: Planning and Design Guidelines*. Report No. PG 2/85, Carried out by the De Leuw Cather Inc., Braamfontein, Johannesburg, September 1985.

Dubrofsky, E. (2009). *Homography Estimation*. Masters essay, The University of British Columbia, Faculty of Graduate Studies in Computer Science, Vancouver, March 2009.

European Commission, (1999). *Passengers' Accessibility of Heavy Rail Systems*. European Cooperation in the Field of Scientific and Technical Research. COST 335, Final Report of the Action, Directorate General Transport, 1999.

Fruin, J.J. (1984). *Crowd Dynamics and Auditorium Management*. Article in Auditorium News published by the International Association of Auditorium Managers, May 1984.

Fridman, N. & Kaminka, G.A. (2007). *Towards a Cognitive Model of Crowd Behaviour Based on Social Comparison Theory*. In Proceedings of the 22nd National Conference on Artificial Intelligence (AAAI-07), 2007.

Fujiyama, T. (2004). *Evaluation of Accessible Design of Public Transport Facilities*. Research Progress Report, Centre for Transport Studies, University College London, United Kingdom, June 2004.

Galea, E.R., Sharp, G. & Lawrence, P.J. (2008). *Investigating the Representation of Merging Behaviour at the Floor-Stair Interface in Computer Simulations of Multi-Floor Building Evacuations*. In Journal of Fire Protection Engineering, 23 July 2008.

The Aqua Group, (1984). *Fire and Buildings*. Granada Publishing Ltd., London.

Goto, T. (2001). *New Stations based on Philosophical Reunion of Diversified Technologies*. In Japan Railway and Transport Review, 28 September 2001.

Grunwald, P. (2005). *Advances in Minimum Description Length: Theory and Applications*. In Cambridge, Mass.; London : MIT Press, p.16, 2005

Helbing, D., Molnár, P. & Schweitzer F. (1994). *Computer Simulations of Pedestrian Dynamics and Trail Formation*. In Evolution of Natural Structures (Sonderforschungsbereich 230, Stuttgart), pp. 229 – 234.

Helbing, D., Schweitzer, F., Keltsch, J. & Molnár, P. (1997) *Active Walker Model for the Formation of Human and Animal Trail Systems*. Physical Review E 56, pp. 2527 - 2539.

Helbing, D., Farkas, I.J. & Vicsek, T. (2000). *Freezing by Heating in a Driven Mesoscopic System*. Physical Review Letters, Volume 84, No. 6, The American Physical Society, 7 February 2000, pp. 1240 – 1243.

Hill, B. (1995). *Changing Stations*. In the December issue of the Japan Railway & Transport Review Magazine, December 1995.

Hofstede, E. (2009) *Constructing a Good Dissertation: A Practical Guide to finishing a Masters, MBA or PhD on Schedule*. ISBN 0-9585007-1-1, Published by EPE, Johannesburg, South Africa.

Hoogendoorn, S. P., Hauser, M. & Rodrigues, N. (2004). *Applying Microscopic Pedestrian Flow Simulation to Railway Station Design Evaluation in Lisbon, Portugal.* Transportation Research Record: Journal of the Transportation Research Board. No. 1878, TRB, National Research Council, Washington D.C., 2004, pp. 83 - 94.

Howes, D.M, Kennedy, M. & Gould, R. (1994). *An Approach to Enhance Rail Travel: A Metropolitan Perspective*. In Proceedings of the Annual Transportation Convention, Rail Transport Session 1C, Pretoria, 1994.

Hye, P.J. (2007). *A Design of Pedestrian Space as an Interactive Space*. International Association of Societies of Design Research, The Hong Kong Polytechnic University, 12 – 15 November 2007.

Jacobs, B.N. (2005). *Improving Accessibility to Commuter Rail Services. Case Study: Khayelitsha Rail Line Extension*. In Proceedings of the 24th Southern African Transport Conference (SATC), Pretoria, July 2005.

Johansson, A., Helbing, D. & Shukla, P.K. (2007). *Specification of a Microscopic Pedestrian Model by Evolutionary Adjustment to Video Tracking Data*. Journal of Advances in Complex Systems (ACS), Volume 10, Supplementary Issue 2 (2007), pp. 271 – 288.

Kandee, S. (2001). *Intermodal Concept in Railway Station Design*. In BU Academic Review, no. 3, 2001, p12.

Kitazawa, K. & Batty, M. (2004). *Pedestrian Behaviour Modelling: An Application to Retail Movements using a Genetic Algorithm.* In J.P. van Leeuwen and H.J.P. Timmermans (eds.) Developments in Design & Decision Support Systems in Architeccture and Urban Planning. Eindhoven University of Technology, Eindhoven.

Kwon, T.J. (2007). *Do Different Urban Configurations Alter Pedestrians' Perceptions? A Morphological Approach to Walkability in the Virtual Reality Urban Setting*. Doctoral dissertation, The University of Michigan, 2007. Faculty of Urban, Technological and Environmental Planning, USA.

Litman, T.A. (2003). *Economic Value of Walkability*. In Proceedings of the 82nd Annual Meeting, Transportation Research Board, Paper 03-2731, Washington D.C., January 2003.

Makgati C.K. (2008). *The Impact of the RSR on Rail Operations: Challenges on Safety Performance and Data Analysis.* International Rail Safety Conference, IRSC 2008, Denver, Colorado, USA.

Meacham, B., Lord, J., Moore, A., Fahy, R., Proulx, G. & Notarianni, K. (2004). *Investigation of Uncertainty in Egress Models and Data*. In Proceedings of the 3rd International Symposium on Human Behaviour in Fire, pp. 419 – 428. Belfast, UK.

Milazzo II, J.S. (1996). *The Effect of Pedestrians on the Capacity of Signalized Intersections*. Master's Thesis, North Carolina State University, Raleigh.

Mounsey, G., McPherson, C. & Langdon, N. (2007). *Pedestrian Planning for the 2006 Commonwealth Games.* In Proceedings of the Institution of Civil Engineers, Municipal Engineers, ISSN 0965-0903, 2007 Vol. 160, No. 4, pp. 177 – 186.

Narasimhan, S. (2007). *Simulation and Optimized Scheduling of Pedestrian Traffic – From Geometric Modelling to Pedestrian Navigation*. Doctoral dissertation, University of Stuttgart, 2007. Fakultät Informatik, Elektrotechnik und Inforationstechnik der Universität Stuttgart, Germany.

Naudé, S., Jones, J. & Louw, P. (2005). *Design Guidelines for Public Transport Facilities*. In Proceedings of the 24th Southern African Transport Conference (SATC 2005). ISBN: 1-920-01712-7, 11-13 July 2005, Pretoria.

Neal, R. M. (1996). *Bayesian Learning for Neural Networks*. Lecture Notes in Statistics No. 118, New York: Springer-Verlag, 1996.

New South Wales (NSW) Ministry of Transport (2008). *Guidelines for the Development of Public Transport Interchange Facilities*. Issue September 2008, Australia.

Nomico, M. & Sanders, P. (2003). *Dichotomies of Urban Change in Durban*. Urban Design International 8(4), pp. 207-222. Accessed from http://eprints.qut.edu.au.

Pan, X., Han, C.S. & Law, K.H. (2005). *A Multi-Agent Based Simulation Framework for the Study of Human and Social Behaviour in Egress Analysis*. In Proceedings of the 2005 International Computing in Civil Engineering Conference, 12- 15 July 2005, Cancun, Mexico.

Paris, S., Donikian, S. & Bonavalet, N. (2006). *Environmental Abstraction and Path Planning Techniques for Realistic Crowd Simulation*. In Computer Animation and Virtual Worlds, Volume 14, Issue 3-4 (July 2006), ISSN:1546-4261, pp. 325 – 335.

Pelechano, N., O'Brien, K., Silverman, B. & Badler, N. (2005). *Crowd Simulation Incorporating Agent Psychological Models, Roles and Communication*. In Proceedings of the 1st International Workshop on Crowd Simulation (2005), pp. 21-30.

Phillips, R., Karachepone, J. & Landis, B. (2001). *Multi-Modal Quality of Service Project.* The Florida Department of Transportation, 2001.

Ribbonaar, D. & Verster, B. (2004). *A Disabling Public Transport System*. In Proceedings of the 23rd Southern African Transport Conference (SATC 2004), ISBN:1-920-01723-2, 12 – 15 July 2004.

Rivasplata, C.R. (2001). *Intermodal Transport Centres: Towards Establishing Criteria*. In Proceedings of the 20th Southern African Transport Conference (SATC 2001), Pretoria, July 2001.

Romer, R.T. (1995). *An Integrated Systems Methodology for Pedestrian Traffic Flow Analysis*. Masters dissertation, University of Nevada, Las Vegas, Department of Civil and Environmental Engineering, USA.

Ronald, N., Sterling, L. & Kirley, M. (2005). *A Conceptual Framework for Specifying and Developing Pedestrian Models*. Department of Computer Science and Software Engineering, The University of Melbourne, Victoria, Australia.

Ronald, N., Sterling, L. & Kirley, M. (2006). *An Agent-Based Approach to Modelling Pedestrian Behaviour*. ISSN 1473-804x online, Department of Computer Science and Software Engineering, The University of Melbourne, Victoria, Australia.

Rontiris, K. (1989). *Guidelines for the Design of Kombi-taxi Facilities*. Research Report No. 88/140/1, Van Niekerk, Kleyn & Edwards (VKE), June 1989.

Rotton, J., Shatts, M. & Standers, R. (1990). *Temperature and Pedestrian Tempo: Walking without Awareness*. Environment and Behaviour, 22, pp. 650 – 674.

Savrasovs, M. (2010). *Mesoscopic Simulation Concept for Transport Corridors*. In Proceedings of the 12th World Conference on Transport Research (WCTR), Lisbon, Portugal, 11-15 July 2010.

Schalekamp, H.V. (2007). *Towards a User-Oriented Approach in the Design and Planning of Public Transport Interchanges*. Master dissertation submitted to the University of Cape Town, August 2007.

Schmitt, A. & Atzwanger, K. (1995). *Walking Fast – Ranking High: A Sociobiological Perspective on Pace*. Ethology and Sociobiology 16, pp. 451 - 462.

Schmittwilken, J., Saatkamp, J., Förstner, W., Kolbe, T. & Plümer, L. (2007). *A Semantic Model of Stairs in Building Collars*. Photogrammetrie, Fernerkundung, Geoinformation PFG, 2007. Heft 6, S.415-428.

Shao, W. (2006). *Animating Autonomous Pedestrians*. Doctoral dissertation, New York University, Department of Computer Science, Courant Institute of Mathematical Sciences, New York University January 2006.

Sound Transit, (2007). *Design Standards and Guidelines for Sound Transit Projects: Sounder & ST Express Passenger Facilities.* For Reference only, Not a Controlled Copy. Prepared by Parson Brinckerhoff Quade & Douglas, Inc., Version 1, 22 January 2007.

South African Rail Commuter Corporation Ltd. (SARCC), (2001). *Towards Improving the Accessibility of Commuter Rail to Special Needs Customers in the Cape Metropolitan Area*. SARCC/CA 9248, Draft Policy Document, Project No. JA0367A, April 2001.

South African Rail Commuter Corporation Ltd. (SARCC), (2003). *Special Needs Passengers Policy for Commuter Rail in South Africa: National Policy Document*. SARCC Report SARCC/CA 1201, June 2003.

South African Rail Commuter Corporation Ltd. (SARCC), (2007a). *Station Walkways and Waiting Areas Design & Assessment Guideline*. For Use on Metrorail Commuter Stations, SARCC Report SARCC001SDS0050A, Revision A, February 2007.

South African Rail Commuter Corporation Ltd. (SARCC), (2007b). *Station Partial Design & Assessment Guideline*. For Use on Metrorail Commuter Stations, SARCC Report SARCC001SDG0060A, Revision A, March 2007.

Srbljinović, A. & Škunca, O. (2003). *An Introduction to Agent Based Modelling and Simulation of Social Processes*. Interdisciplinary Description of Complex Systems 1(1-2), 1-8, Zagreb, Croatia.

StatSoft, Inc. (1998). *STATISTICA for Windows* [Computer program manual]. Tulsa, OK: StatSoft, Inc., 2300 East 14th Street, Tulsa, OK 74104, phone: (918) 749-1119, fax: (918) 749-2217, email: info@statsoft.com, WEB: http://www.statsoft.com.

Suzuki, T. (1995). *A Vision of Future Railway Stations*. In the December issue of the Japan Railway & Transport Review Magazine, December 1995.

Teknomo, K. (2006). *Micro-Pedsim User Manual*. Version 1.3.

Templer, J.A. (1975). *Stair Shape and Human Movement*. Doctoral dissertation, Columbia University, 1975. Graduate School of Arts and Sciences, Columbia University, USA.

Tolley, R., Bickerstaff, K. & Lumsdon, L. (2001). *What do Experts Have to Say about the Social and Cultural Influences on Walking Futures?*. In Australia: Walking the 21st Century, Perth, Western Australia, 20 to 22 February 2001.

Toyama, M.C., Bazzan, A.L.C. & da Silva, R. (2006). *An Agent-Based Simulation of Pedestrian Dynamics: from Lane Formation to Auditorium Evacuation*. In Proceedings of the 5th International Joint Conference on Autonomous Agents and Multi-agent Systems, Simulation and modelling session, ISBNL1-59593-303-4, Hakodate, Japan.

Tsuji, Y. (2003). *Numerical Simulation of Flow at High Densities*. In proceedings for Pedestrian and Evacuation Dynamics, University of Greenwich.

Union Carriage & Wagon Company (Pty) Ltd. (1983). *Class 5M2A, 3kV, D.C. Suburban Stock Maintenance Manual.* 6 June 1983.

Van As, S.C. & Joubert, H.S. (1995). *Applied Statistics for Civil Engineers*. Department of Civil Engineering, University of Pretoria, Pretoria.

Vanderschuren, M. (2007). *Calibrating Microscopic Simulation Models*. In Proceedings of the 26th Southern African Transport conference (SATC 2007), ISBN No. 1-920-01702-X, Pretoria, 9 – 12 July 2007.

Van Hagen, M. & Scheffer, P. (2005). *Perception of Quality at Stations: A New Method for Calculating the Experienced Value of Quality*, In proceedings of the European Transport Congress, Strasbourg, 5 October 2005.

Victor, D.J. (1989). *Pedestrian Traffic Management in Indian Cities*. In the 5th World Conference on Transport Research, July, Yokohama, Japan.

Washington Metropolitan Area Transit Authority (WMATA), (2005). *Guidelines for Station Site and Access Planning*. Department of Planning and Information Technology, Office of Business Planning and Project Development, Final Draft, August 2005.

Witte, A.L. (2001). *Cross-Cultural Study of Pace of Life on Two Campuses*. Journal of Psychological Inquiry 6, pp. 84 - 88.

Zhang, J., Wang, H. & Li, P. (2003). *Cellular Automata Modelling of Pedestrian's Crossing Dynamics*. Journal of Zhejiang University SCIENCE, ISSN 1009-3095, Hangzhou, China.

10. ABOUT THE AUTHOR

Laurent is as an Associate heading up the Transportation Division in the Cape Town Office for Goba Consulting Engineer (Pty) Ltd and has over 20 years' experience in varied traffic and transportation projects as well as numerous public transport projects.

Laurent graduated with a BSc. (Civil) degree from the University of Cape Town in 1991 and started his career at the then Cape Provincial Administration before heading off to Pretoria in 1994 to become involved in the RDP projects at the time working with Bouwer Viljoen Consulting Engineers. In 1997, Laurent joined Tolpan Consulting Engineers and was involved with several specialist Toll Road Feasibility and related studies, which were conducted primarily for the South African National Roads Agency.

Over the last few years, Laurent has been involved with rail station design at a project and technical review level for SARCC/Intersite and private consultants and has developed a macroscopic model for the determination of first-order station dimensions. The model has since been applied to the development plans for the Khayelitsha, Langa, Nyanga, Athlone and Heideveld stations in Cape Town.

Laurent's current Ph.D research activities conducted through the University of Stellenbosch, lies in the design evaluation of rail stations based on local pedestrian characteristics and believes that international design standards and codes may not be the most appropriate due to the cultural diversity experienced at local stations. Laurent also holds a B.Eng (Transportation) degree from the University of Pretoria and an MSc. (Civil) cum laude degree from the University of Stellenbosch.

11. APPENDIX A: APPROVED PH.D PROPOSAL

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THE DEVELOPMENT OF A CALIBRATED SPATIAL PARAMETERS (SP) MODEL TOWARDS THE DESIGN OF METRO RAILWAY STATIONS IN SOUTH AFRICA

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PhD (Civil) Proposal Submission

Promoter : PROF. CHRISTO BESTER

15 May 2008

TABLE OF CONTENTS **PAGE**

LIST OF FIGURES

1. BACKGROUND

Intersite Property Management Services, together with the South African Rail Commuter Corporation (SARCC) who own and operate all stations, have recently embarked on a country wide programme to upgrade commuter rail stations in South Africa as part of a larger process towards improving the commuter rail service in the country. The impending FIFA 2010 World Cup event has led to a revision of priorities and provides further impetus to improve the levels of service to public transport users both for current every day users as well as visitors to the country.

The long standing lack of infrastructure investment over many years has not only resulted in a declining service and loss in patronage (City of Cape Town, 2006), but has led to a lapse in design philosophies (with particular reference to station design) in South Africa. The recent budgetary allocations to station re-design and construction, after many years of inactivity in this area, has resulted in adopting outdated design guidelines. It is the intention that this PhD research develops a Spatial Parameters (SP)-model which contributes towards the design of South African Metro railway stations. The model will also allow design checks to be made with the added benefit that the design approvals processes can be more speedily handled.

The researcher has been fortunate to be directly involved in the transportation aspects of the Athlone, Heideveld and Langa railway station upgrades through an appointment with the SARCC since February 2007. During the course of this time, the researcher has contributed to the field of South African station design by developing a Spatial Parameters (SP) matrix which has since been utilised for the ultimate design of the Athlone, Heideveld and Langa (AHL) Stations.

The layout of this PhD proposal document first describes the current problems associated with the South African station design process in Chapter 2. Chapter 3 discusses the main component (ie. the development of the Spatial Parameters Model) forming the focus of the proposed study. A brief discussion on the necessity for pedestrian modelling is discussed in Chapter 4. Chapter 5 provides the research aims and intended methodology and Chapter 6 provides a proposed research programme to fulfil the study aims and objectives.

2. DESCRIPTION OF THE STATION DESIGN PROCESS PROBLEM

2.1 Introduction

Anecdotal evidence (GOBA, 2008) suggests that poor infrastructure design increases Public Transport (PT) operating costs by as much as 20 per cent. The provision of efficient and integrated station infrastructure through an optimum design and standardised guideline processes, providing appropriate Levels of Service, is therefore considered of paramount importance towards the current and future successes of South African station design.

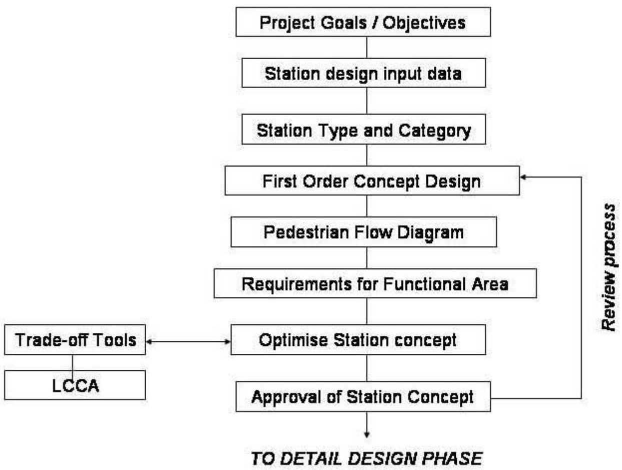
2.2 Existing Station Design Process and Problems

Station design in South Africa is based on an eleven year old Norms, Guidelines and Standards (NGS) document (SARCC, 1997). Since then, changes in legislation and technology have changed the design principles recommended in this document. For example, new legislation requirements including the accommodation of Special Needs Passengers (SNP's) has significantly changed the design philosophy with regard to pedestrian accessibility. This aspect is important when one considers that an estimated 33% (Stanbury et al & Jacobs, 2005) of the user population are SNP's.

The development of SNP user requirements and design standards is relatively new to South Africa and was first introduced in the Khayelitsha Station 4/4A and Lentegeur Station designs (Jacobs, 2005). The operational functionality of the designs however *still needs to be assessed*.

The description of the SARCC Feasibility / Concept design stage as outlined in the NGS document is shown in Figure 1. The "*First Order Concept Design*" consists of a proposed station block diagram, which according to the design process, needs to be optimised before the station concept is approved.

Figure 1 : SARCC Feasibility / Concept Station Design Phase (Source : SARCC, 1997)



The NGS document mentions that "*all design characteristics shall be identified and the determination of the specific parameter per station shall be according to the <u>prescribed method</u> or <u>any acceptable transport engineering method</u>. Some of the methods (models/procedures) is however currently in the process of normalisation and finalisation*" (SARCC, 1997).

There are two problems with this general guideline. Firstly, there are no set "*prescribed methods or models/procedures*" proposed in the document. Secondly, the general guideline, "*any acceptable transport* *engineering method*" in the determination of station functional areas *is unclear* and therefore open to varied assessment techniques and results making the (client) review process complicated and lengthy. In the design process of the Khayelitsha Stations 4 and 4A, the consultant design report indicated that the "*NGS document is vague*" and "*there is no guidance on the spatial provisions of the concourse in the NGS and similarly, the spatial requirements for queuing at the ticket office.*" (A3 Transportation Engineers et al, 2004). During the course of the AHL design process, it has become clear to the researcher and the client body (SARCC/Intersite), that the station design process is lacking, offers varying outputs, is not rigid and is in the process of "evolving".

2.3 The "Evolving" Station Design Process

With the recent intention by the SARCC to upgrade the AHL Stations, the design process will, for the first time in South Africa, incorporate pedestrian modelling. The outcome of the pedestrian modelling on station design is however, at this early stage of the research, unknown.

The researcher believes there is a definitive role for a SP-model which will provide the initial spatial parameters to a station design. It is intended that the SP-model will be calibrated using actual surveyed observations and pedestrian modelling outputs, which then incorporates the integration of pedestrian functioning into the model. The more accurate the model, the less likely lengthy review processes are required.

It is proposed through this PhD research that the new "evolving" process of railway station design incorporate the use of the SP-model for the "*Requirements for Functional Area*" and "*Review Process*" as shown earlier in Figure 1. It is believed that the benefits of including SP-modelling to the current design process will improve station design in South Africa.

3. DEVELOPMENT OF A SPATIAL PARAMETERS (SP) MODEL

3.1 Background to the formulation of the SP-Matrix

As indicated in Chapter 1, the researcher has developed a SP-matrix as part of the AHL Stations project since project inception in February 2007. The matrix was essentially borne out of a lack of clear design direction in the NGS documentation. The SP-matrix is a MS-Excel based spreadsheet that was developed to calculate station infrastructure sizing requirements in order to accommodate the station design peak one-minute flow rate at acceptable levels of service. As there are dependant relationships between certain spatial parameters, the spreadsheet proved to be a useful tool. The SP-matrix spreadsheet incorporates traffic engineering, pedestrian flow theory, queuing theory and Level of Service criteria (HCM, 2000).

The SP-matrix (version 05) became the benchmark model for the design of the AHL stations although it is acknowledged that the Spatial Parameters matrix is also still evolving and its outputs are not to be considered as rigid spatial requirements.

3.2 Revisions to the SP-Matrix since Project Inception

The SP-matrix has, since February 2007, undergone several revisions culminating in a version 05 status, dated 8 October 2007. This matrix was finally approved by the SARCC after a formal presentation by the researcher to SARCC/Intersite stakeholders on 23 January 2008.

The successive revision outputs of the SP-matrix (together with cost estimation revisions dependant on these outcomes) became the major driver of the "*Review Process*" as indicated in Figure 1. At the presentation meeting of 23 January 2008, shortcomings in the SP-matrix (version 05) was revealed and further deficiencies are continually being highlighted and exposed by the Architects as the detail design process continues. The transportation appointment has however ended and hence the objective of the proposed PhD research is thus to elaborate and update the model to eliminate deficiencies and cover all technical aspects in detail.

Deficiencies exposed by the researcher in earlier versions of the SP-matrix (J&G, 2007a) and the subsequent review of the matrix to a version 05 (J&G, 2007b) resulted in a significant reduction in AHL concourse sizing requirements resulting in considerable cost savings to the client. Resulting from the recent significant savings effected by way of SP-matrix outputs, the SARCC commissioned, in April 2008, a pedestrian modelling exercise with two primary objectives in mind as follows:

- To confirm the spatial requirements determined by the SP-matrix (version 05).
- To amend or "fine tune" the final design as required eg. pinch points, integration of functions etc.

3.3 Spatial Parameters Model Research and Study Focus

It is the intention that this PhD research proposal will further refine and develop the SP-"matrix" to a generic SP-"model" to allow for diverse applications which is sensitive to input variations and environments. Although the approach is essentially based upon overhead concourse stations, it is intended that the model be sufficiently "generic" to consider different station configurations (including side facing platforms & island platform arrangements) where the physical constraints have the potential to negatively impact on operational performance. This specifically relates to the spatial treatment of access arrangements (platform access, evacuation etc). The potential also exists to apply the model to the audit of existing facilities to fundamentally guide station upgrading / remodelling requirements and associated user requirements.

The outputs of the pedestrian modelling will be used to calibrate the SP-model results where appropriate, such that it accounts for the integration of pedestrian functions. This will ultimately allow for a more confident use of the SP-model and reduce the optimising and review process time.

It is also intended that the SP-model go through a further calibration process be means of evaluating the operational parameters of fully functioning concourse railway stations. The influence of public markets and other informal businesses may be an additional attribute necessary to be factored into the SP-model.

4. PEDESTRIAN MICROSCOPIC SIMULATION MODELLING

Up until recently, pedestrian microscopic modelling has not been incorporated into the design of railway stations in South Africa. The recent developments in station design described in the previous sections have led to the incorporation of such modelling to assist/augment and confirm the spatial designs. The impact, usefulness and shortcomings of such pedestrian modelling in the South African context has not yet been determined. The sensitivity and alignment of pedestrian modelling outputs to the SP-model outputs is of key interest to the researcher and will form a major informant to the SP-model.

5. RESEARCH AIMS AND METHODOLOGY

5.1 Introduction

It is proposed that the SP-model to be developed in this research be used as a tool in order to dimension "*concept block diagrams*" for approval, which depending on research results, will require appropriate calibration using the results of real life surveys and pedestrian modeling.

5.2 Objectives of the study

The specific objective of this proposed research is to develop the existing Spatial Parameters Matrix (SP-matrix) into a generic SP-model that can be applied, with a greater degree of confidence, to any proposed new or upgraded railway station that will then better inform station infrastructure dimensioning requirements.

The current status of the limited SP-matrix is that it has not been calibrated against pedestrian modeling or real life South African behavioural conditions. There is a therefore a great risk to stakeholders that the station is either under designed (to the discomfort of users) or over designed (at unnecessary expense to the client). It is also envisaged that the SP-model provides a toolkit to stakeholders and clients enabling the checking of designs provided by consulting practitioners.

The SP-model is to be developed to ensure that all design parameters are sized sufficiently to accommodate suitable passenger levels of service for the ultimate design. Each of the station spatial components has an effect on the Level of Service that passengers experience and indeed there is an interaction between them.

The objectives of the pedestrian simulation is to achieve the following:-

- Determine the impact on design when pedestrian functions are integrated.
- Provide a means to calibrate the SP-model.
- Determine pedestrian modelling deficiencies and account for this in the SP-model (if possible).

5.3 Overall Study Approach (Methodology)

The proposed methodology used to achieve the PhD thesis objectives is as follows :

1. Review and finalise thesis concept, objectives and methodologies with Supervisor.

2. Undertake a literature review on current local practice (SARCC, Gautrain etc.) and International best practice. Undertake overseas trip to Europe and meet with various rail infrastructure Authorities and consulting firms specialising in rail infrastructure. Make personal observations at concourse type stations in the UK if possible.

3. Undertake field surveys at existing stations in Cape Town. It is anticipated that the station surveys will provide insight with regard to principles previously used for station building accommodation, ramp and stair design and access control systems currently in use. The design success/failures of incorporating universal accessibility at local stations will be evaluated. It is also intended that the impact of bicycle use within the station functional area, as well as the simultaneous use of SNP ramps by able-bodied persons, will be observed and assessed. Other surveys planned (but not limited to) include the observation of peak hour ticket sale rates and turnstile capacity.

4. It is intended that all station surveys (conducted both locally and internationally) will be video recorded during the peak times for analysis later. This allows detailed desktop analysis to be undertaken via time delay or fast forward replay techniques.

5. Build a pedestrian model for an existing station/s and calibrate. Correlate and evaluate findings of the pedestrian model and SP-model for the selected station/s. Conduct a similar exercise for the AHL stations.

6. Identify and address deficiencies in the SP-model.

7. Undertake additional behavioural field surveys at selected stations in Cape Town to address deficiencies. For example, it may be necessary that surveys be conducted which observes the impact of location of the concourse to platform stairs on train boarding/alighting and the study may extend to determine the impact of stair location of several stations along a particular line. The impact of the Metro and Metro Plus carriage proximity to staircases may also need to be evaluated.

8. Produce a versatile Spatial Parameters model that is calibrated against visual observations and pedestrian modeling outputs.

9. Compile and submit a draft PhD thesis report for approval prior to final submission.

5.4 Academic Contribution

The primary academic contribution of the research will be to develop and demonstrate the benefit of a *SP-model which will assist in the determination of spatial parameters of Metro railway stations in South Africa*. It is anticipated that the research will contribute towards cost effective and efficient station planning and design in South Africa.

5.5 Research Originality

It is anticipated that the final SP model produced will primarily be suited for application to commute type environments viz. rail concourse line stations operating under high volume pulse loading conditions. The concepts applied in the model however could be expanded to incorporate other types of transport facilities eg. airports but this would require considerable further research as these facilities operate under different conditions and are not typical commute environments such as that encountered at Metro railway stations.

Internationally, station design incorporates traffic (pedestrian) engineering principles in the determination of spatial parameters which are then checked against pedestrian modelling results. The problem is that the spatial parameters are individually determined based on independent calculations. The interdependencies of the parameters under operating conditions are however only checked with pedestrian modelling, where design alterations to the spatial parameters are then done. What is unique about the SP model, despite the fact that no such model exists (to the best knowledge of the researcher), is that it will attempt to incorporate both calculation and integration functions into one model viz. engineering “level of service” based calculation and integral spatial calibration.

In South Africa, the same station design principle as used internationally applies, but thusfar without the benefit of pedestrian modelling. Pedestrian modelling has only recently been introduced to South African station design in 2008. Pedestrian behaviour, informal trading activity, multi-class carriages etc. are some of the factors unique to South African conditions proposed to be incorporated into the model.

6. PROPOSED PROGRAMME

The PhD project is based on the following proposed program :

Proposed PhD Programme			
No	**Activity/Assignment**	**Date**	**Outputs**
1	Initial Literature review and research on PhD topic. Prepare PhD application. Acceptance of topic. Formally register for PhD study at University.	2008	PhD Application proposal.
2	Literature Review: Local & International Literature review on Station design standards. International best-practice. Preliminary update of SP-matrix to SP-model.	2008	Interim Literature review report.
3	Data Collection: Overseas fact-finding trip and personal station		

Proposed PhD Programme			
No	**Activity/Assignment**	**Date**	**Outputs**
	observations (UK). Undertake local station field measurements: Establish base data and subsequent data sources and collection methodology. Observe station design infrastructure success and failures including observations with regard to universal access.	2008/2009	Interim status report (Station survey results)
4	Detailed SP-Model development and calibration: Refine SP-model for integrated station functioning using pedestrian model and field survey results. Adapt model for varied input attributes.	2008/2009	Interim status report (SP-model development), including the findings of the station field surveys) as a *First Publication of the Research*
5	Application of Model: Preliminary application of SP-model to fully functional stations. Identify outstanding deficiencies in the SP-model and propose methods to address these.	2009	
6	SP-Model refinement: Conduct additional pedestrian surveys at stations (and/or pedestrian modelling) as identified to address model deficiencies. Further re-fine model based on results of these surveys.	2009/10	Submission of paper (describing the application and benefits of SP-modelling in station design) as a *Second Publication of the Research*
7	Complete additional research aspects identified during the course of the research. Write up Draft thesis and submit for review before submission.	2010	Draft thesis Final thesis PhD Presentation

6.1 Papers

The exact content of presentations and publications at this stage is not known, but the following two papers are possible suggestions:

First Publication of the Research : *"Critical assessment of the design of concourse type railway stations in South Africa"*. This paper will describe the findings of the field surveys conducted, focussing on the deficiencies of existing concourse station infrastructure and the successes/failures of universal access design. The paper will show the criteria currently used in station design and will highlight the shortcomings of the design process and the future research envisaged by the researcher in addressing these issues. The role of the SP-model is to be introduced.

Second Publication of the Research : *"The development, refinement and application of the SP-model towards optimised Metro concourse railway station design in South Africa"*. This paper builds on the research presented in the first paper and elaborates on the analysis methodologies and calibration techniques used to achieve an integrated model that can be used with confidence for determining cost effective and efficient spatial parameters for concourse based railway stations in South Africa.

6.2 Conclusion

It is intended that the output of this research project will provide a model for confidently providing the spatial requirements for concourse station facilities, which conforms to pedestrian modelling and actual pedestrian behaviour and significantly reduces the optimising time and cost required for approving station designs.

7. REFERENCES

1. **A3 Transportation Engineers, 2004.** *"Khayelitsha Rail Extension: Definition of User Requirements, Stations 4 & 4A"*. Preliminary Design report carried out in association with Target Projects, Magqwaka Assoc Arch, Ngewu & Assoc, Brent Samson & Assoc and Manong & Assoc for SARCC, Report No : SARCC/SMP/CA1219, File No. AM/SMP/4/2/1/5, Cape Town, 1 June 2004.

2. **ACG Architects and Development Planners and KMH Architects, 2008.** *"Philippi Station Stage 3 Design"*. Carried out for Intersite Property Management Services and SARCC, Cape Town, 25 March 2008.

3. **Cape Metropolitan Council (CMC), 1999.** *"Moving Ahead, Cape Metropolitan Transport Plan, Part 2: Public Transport Strategic Component"*. Discussion Document produced by the Cape Metropolitan Council, Cape Town, September 1999

4. **City of Cape Town, 2002.** *"Public Transport Cost Model"*. Produced by Stewart Scott Inc and Del Mistro R. as part of the Cape Town Public Transport Restructuring Programme, CMC Administration, Roads and Stormwater Branch, Cape Town, May 2002

5. **City of Cape Town (CPTR), 2004.** *"Summary of 2004/5 Current Public Transport Record"*. Produced by the City of Cape Town, Transport, Roads and Stormwater Branch, Cape Town, 2004/5

6. **City of Cape Town, 2006.** *"Rail Framework"*. Draft report produced by Asakhe Consulting Engineers, Cape Town, 2006

7. **Del Mistro R.F, 1987.** *"Guidelines for the Provision of Public Transport Facilities for Developing Countries"*. Carried out by the Transport Planning & Development Group, NITRR/CSIR, Department of Transport, Pretoria, August 1987.

8. **Department of Transport (DOT), 1994.** *"Integration of Inter and Intra-City Transport at Points of Mode Transfer"*. Report No. RR 93/665, Carried out by the Division of Roads and Transport, CSIR, Pretoria, July 1994.

9. **GOBA (Pty) Ltd, 2008.** *"Athlone, Langa, Heideveld Commuter Station Upgrade : Western Cape Pedestrian Simulation : Project Proposal"*. Project proposal prepared for Jeffares and Green (Pty) Ltd, March 2008.

10. **Schalekamp H.V, 2007.** *"Towards a User-Oriented Approach in the Design and Planning of Public Transport Interchanges"*. Master dissertation submitted to the University of Stellenbosch, August 2007.

11. **Highway Capacity Manual (HCM), 2000.** Transportation Research Board, Washington D.C. 2000.

12. **Jacobs B.N, 2005.** "*Improving Accessibility to Commuter Rail Services. Case Study : Khayelitsha Rail Line Extension*". Paper presented at the 24th Southern African Transport Conference (SATC), Pretoria, July 2005.

13. **Jeffares & Green (Pty) Ltd (J&G), 2007a.** "*Review of Langa Station Accommodation Requirements and comparison with Khayelitsha Station 4 and Phillipi Station*". Interim Paper prepared and distributed for project purposes. Cape Town, 1 October 2007.

14. **Jeffares & Green (Pty) Ltd (J&G), 2007b.** "*Review of Spatial Parameters Matrices (From Revision 03 to Revision 05)*". Interim Paper prepared and distributed for project purposes. Cape Town, 8 October 2007.

15. **Jeffares and Green (Pty) Ltd (J&G), 2008.** "*Transportation Report : Upgrade of Athlone, Heideveld and Langa Train stations*". Report Stage/Appraisal and Definition, Report prepared for the South African Rail Commuter Corporation Ltd, Intersite Property Management Services and Metrorail, January 2008.

16. **Jonker and Barnes Architects (J&B), 2007.** "*Urban Review Report ; Upgrade of Athlone, Heideveld and Langa Train Stations*". Report produced for the South African Rail Commuter Corporation Ltd, Intersite Property Management Services and Metrorail, 2007 .

17. **Provincial Government : Western Cape (PGWC), 2004.** "*Provincial Land Transport Framework*". Western Cape Department of Transport and Public Works, 2004.

18. **Rivasplata C.R, 2001.** "*Intermodal Transport Centres : Towards establishing Criteria*". Paper presented at the 20th Southern African Transport Conference (SATC), Pretoria, July 2001.

19. **South African Rail Commuter Corporation Ltd (SARCC), 1997.** "*Metro Station Acquisition: Norms, Guidelines and Standards*". Prepared by Propenta (Pty) Ltd Engineering and Project Management and Protekon Architects, October 1997.

20. **South African Rail Commuter Corporation Ltd (SARCC), 2001.** "*Towards Improving the Accessibility of Commuter Rail to Special Needs Customers in the Cape Metropolitan Area*". (SARCC/CA 9248. Draft Policy Document, Project No. JA0367A, April 2001.

21. **Stanbury J. and Scott I, 2005.** "*Towards Improving the Accessibility of Commuter Rail to Special Needs Passengers*". Paper presented at the 24th Southern African Transport Conference (SATC), Pretoria, July 2005.

12. APPENDIX B: PRASA CONFIDENTIALITY AGREEMENT

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CONFIDENTIALITY AGREEMENT

- for the purpose of conducting research in the PRASA environment, or using Company information for research purposes

I, the undersigned

1. herewith undertake that all information disclosed or submitted, either orally, in writing or in other tangible or intangible form by PRASA, (its subsidiaries, business units, its employees agents and/or consultants) to me, or made available to me, or details of PRASA's business or interest of which I may become aware of in respect of the research being done by myself for study purposes at STELLENBOSCH (University/~~College~~), to keep confidential and not to divulge to anyone either privately or publicly for which PRASA did not give written consent;
2. guarantee that I will apply the information, detail or knowledge in **clause 1** only for the purpose of my academic research;
3. indemnify PRASA against any claims that may be instituted against it, amounts that may be claimed or losses that PRASA may suffer in consequence of a violation by me of any provision included in this agreement;
4. agree that the provisions of this agreement binds me to PRASA, even if I cease to be a student, employee, representative or advisor of the STELLENBOSCH (University/~~College~~), depending as the case may be after ceasing to be such a person.
5. shall immediately disclose in writing all new information in my possession or under my care relating to the research, provided that such new information must have been developed during the course of the research relating to this agreement.
6. agree that PRASA will have a final say on whether my final work gets published, either in journals, university libraries or any arena where such work may be accessed either electronically or physically. I further accept that PRASA reserves the rights to put limitations on which parts of my work may be published, either in full or in sections. This clause is not applicable to the information that is in the public domain, and/or published in the Annual Reports.

7. undertake to make my Promoter/Supervisor and/or the University/College aware of the terms and conditions of this agreement.

SIGNED at CAPE TOWN on this 26TH day of JANUARY ~~2009~~ 2010.

L Hermant.

Signature

L.F.L. HERMANT.

Name

M de Gersigny

Witnessed by

M.R. DE GERSIGNY

Name

Address 1ST FLOOR, BUILDING A, AVANTI CHURCHILL CLOSE, BELLVILLE metrorail

SITE ACCESS CERTIFICATE

EXPIRY DATE : 31 JANUARY, 2010

SURVEY

Access to : **VARIOUS STATIONS**

Name of Engineer : **GOBA**

Contract / Order No. **16842**

The above-mentioned works site/ area is made available to you for the carrying out of associated works in terms of your agreement with

INTERSITE

Kindly note that you are at all times responsible for the control and safety of the Works Site, and for persons under your control having access to the site.

As from the date hereof you will be responsible for compliance with the requirements of the Occupational health and Safety Act, 1993 (Act 85 of 1993) as amended, and all conditions of the contract pertaining to the site of the works as defined and demarcated in the contract documents including the plans of the site of work areas forming part thereof.

Date : ______________________

Signed : ______________________
Risk Manager

ACKNOWLEDGEMENT OF RECEIPT

I, **L. HERMANT** do hereby acknowledge and accept the duties

and obligations in respect of the Safety of the site/area of Work in terms of the Occupational Health and Safety Act; Act 85 of 1993.

Signature: ______________ Date: 24-02-2009

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13. APPENDIX C: PEDESTRIAN LOS DEFINITION (TRB 1999)

LOS	Visual Representation	Description	Walkways/Skywalks	Stairs	Source
LOS A		At a walkway LOS A, pedestrians move in desired paths without altering their movements in response to other pedestrians. Walking speeds are freely selected, and conflicts between pedestrians are unlikely.	$M > 3.3$ m²/pax $q < 23$ pax/m/min	$M > 1.9$ m²/pax $q < 16$ pax/m/min	TCQSM
			$M > 5.6$ m²/pax $q < 14$ pax/m/min	$M > 1.9$ m²/pax $q < 16$ pax/m/min	HCM 2000
LOS B		At LOS B, there is sufficient area for pedestrians to select walking speeds freely to bypass other pedestrians, and to avoid crossing conflicts. At this level, pedestrians begin to be aware of other pedestrians, and to respond to their presence when electing a walking path.	$2.3 < M < 3.3$ m²/pax $23 < q < 33$ pax/m/min	$1.4 < M < 1.9$ m²/pax $16 < q < 23$ pax/m/min	TCQSM
			$3.7 < M < 5.6$ m²/pax $14 < q < 21$ pax/m/min	$1.6 < M < 1.9$ m²/pax $16 < q < 20$ pax/m/min	HCM 2000
LOS C		At LOS C, space is sufficient for normal walking speeds, and for bypassing other pedestrians in primarily unidirectional streams. Reverse-direction or crossing movements can cause minor conflicts, and speeds and flow rate are somewhat lower.	$1.4 < M < 2.3$ m²/pax $33 < q < 49$ pax/m/min	$0.9 < M < 1.4$ m²/pax $23 < q < 33$ pax/m/min	TCQSM
			$2.2 < M < 3.7$ m²/pax $21 < q < 33$ pax/m/min	$1.1 < M < 1.6$ m²/pax $20 < q < 26$ pax/m/min	HCM 2000
LOS D		At LOS D, freedom to select individual walking speed and to bypass other pedestrians is restricted. Crossing or reverse-flow movements face a high probability of conflict, requiring frequent changes in speed and position. The LOS provides reasonably fluid flow, but friction and interaction between pedestrians is likely.	$0.9 < M < 1.4$ m²/pax $49 < q < 66$ pax/m/min	$0.7 < M < 0.9$ m²/pax $33 < q < 43$ pax/m/min	TCQSM
			$1.4 < M < 2.2$ m²/pax $33 < q < 49$ pax/m/min	$0.7 < M < 1.1$ m²/pax $26 < q < 36$ pax/m/min	HCM 2000
LOS E		At LOS E, virtually all pedestrians restrict their normal walking speed, frequently adjusting their gait. At the lower range, forward movement is possible only by shuffling. Space is not sufficient for passing slower pedestrians. Cross- or reverse-flow movements are possible only with extreme difficulties. Design volumes approach the limit of walkway capacity, with stoppages and interruptions to flow.	$0.5 < M < 0.9$ m²/pax $66 < q < 82$pax/m/min	$0.4 < M < 0.7$ m²/pax $43 < q < 56$ pax/m/min	TCQSM
			$0.75 < M < 1.4$ m²/pax $49 < q < 60$ pax/m/min	$0.5 < M < 0.7$ m²/pax $36 < q < 49$ pax/m/min	HCM 2000

Table C1 : Quantitative definition of level-of-service on walkways

Level-of-service	Space-density (m^2/pax)	Intensity (Pax/m/min)	Speed (m/s)	Guideline	Author (source)
A	> 3.2	< 23	1.30	Fruin	Daamen 2002
B	2.3 – 3.2	23 – 33	1.25		
C	1.4 – 2.3	33 – 49	1.15		
D	0.9 – 1.4	49 – 66	1.00		
E	0.5 – 0.9	66 – 82	0.70		
F	< 0.5	>82			
A	> 5.6	< 14	>1.30	HCM 2000	TRB 2000; Rouphail *et al.* 1998
B	3.7 – 5.6	14 – 21	1.27 – 1.30		
C	2.2 – 3.7	21 - 33	1.22 – 1.27		
D	1.4 – 2.2	33 – 49	1.14 – 1.22		
E	0.75 – 1.4	49 – 60	0.75 – 1.14		
F	< 0.75	Var.	< 0.75		
A	> 3.3	< 23	>1.32	TCQSM	TRB 1999
B	2.3 – 3.3	23 – 33	1.27 – 1.32		
C	1.4 – 2.3	33 - 49	1.22 – 1.27		
D	0.9 – 1.4	49 – 66	1.15 – 1.22		
E	0.5 – 0.9	66 – 82	0.77 – 1.15		
F	< 0.5	Var.	< 0.77		

Table C2 : Quantitative definition of level-of-service on stairs

Level-of-service	Space-density (m^2/pax)	Intensity (Pax/m/min)	Horz Speed (m/s)	Guideline	Author (source)
A	> 1.9	< 16	0.53	HCM 2000	TRB 2000; Rouphail *et al.* 1998
B	1.6 – 1.9	16 – 20	0.53		
C	1.1 – 1.6	20 – 26	0.48		
D	0.7 – 1.1	26 – 36	0.42		
E	0.5 – 0.7	36 – 49	0.40		
F	< 0.5	Var.	< 0.40		
A	> 1.9	< 16		TCQSM	TRB 1999
B	1.4 – 1.9	16 – 23			
C	0.9 – 1.4	23 – 33			
D	0.7 – 0.9	33 – 43			
E	0.4 – 0.7	43 – 56			
F	< 0.4	Var.			

Table C3 : Definition of Level of Service for Queuing Areas

Level-of-service	Space-density (m^2/pax)	Interperson spacing (m)	Guideline	Author (source)
A	< 1.21	> 1.2	HCM 2000	TRB 2000; Rouphail *et al.* 1998
B	0.93 – 1.21	0.9 – 1.2		
C	0.65 – 0.93	0.7 – 0.9		
D	0.27 – 0.65	0.3 – 0.7		
E	0.19 – 0.27	< 0.3		
F	< 0.19	Negligible		
A	< 1.2	> 1.2	TCQSM	TRB 1999
B	0.9 – 1.2	1.1 – 1.2		
C	0.7 – 0.9	0.9 – 1.1		
D	0.3 - 0.7	0.6 – 0.9		
E	0.2 – 0.3	< 0.6		
F	< 0.2	Negligible		

14. APPENDIX D: RESULTS OF INTERNATIONAL PEDESTRIAN EMPIRICAL STUDIES

Table D1 : Free-flow Speed for Stairs (Source: Fruin 1987)

Author	Gender, Age	Direction	Riser, Tread dimension (m)	Stair Gradient (degree angle)	Mean Speed (m/s)
Sample size *n* =7 00 (Commuter Movement) (Note – Unless otherwise indicated, all speeds shown are slope speeds)	Males, Age < 29	Down	0.18 m, 0.29 m	32°	0.98
			0.15 m, 0.30 m	27°	1.04
		Up	0.18 m, 0.29m	32°	0.66
			0.15 m, 0.30 m	27°	0.68
	Females, Age < 29	Down	0.18 m, 0.29 m	32°	0.70
			0.15 m, 0.30 m	27°	0.75
		Up	0.18 m, 0.29 m	32°	0.64
			0.15 m, 0.30 m	27°	0.63
	Average, Age < 29	*Down*	*0.18 m, 0.29 m*	*32°*	*0.90*
			0.15 m, 0.30 m	*27°*	*0.91*
		Up	*0.18 m, 0.29 m*	*32°*	*0.65*
			0.15 m, 0.30 m	*27°*	*0.65*
	Males, 30 < Age < 50	Down	0.18 m, 0.29 m	32°	0.81
			0.15 m, 0.30 m	27°	0.91
		Up	0.18 m, 0.29 m	32°	0.60
			0.15 m, 0.30 m	27°	0.66
	Females, 30 < Age < 50	Down	0.18 m, 0.29 m	32°	0.60
			0.15 m, 0.30 m	27°	0.73
		Up	0.18 m, 0.29 m	32°	0.57
			0.15 m, 0.30 m	27°	0.61
	Average, 30 < Age < 50	*Down*	*0.18 m, 0.29 m*	*32°*	*0.77*
			0.15 m, 0.30 m	*27°*	*0.88*
		Up	*0.18 m, 0.29 m*	*32°*	*0.59*
			0.15 m, 0.30 m	*27°*	*0.65*
	Males, Age > 50	Down	0.18 m, 0.29 m	32°	0.67
			0.15 m, 0.30 m	27°	0.67
		Up	0.18 m, 0.29 m	32°	0.51
			0.15 m, 0.30 m	27°	0.46
	Females, Age > 50	Down	0.18 m, 0.29 m	32°	0.55
			0.15 m, 0.30 m	27°	0.63
		Up	0.18 m, 0.29 m	32°	0.46
			0.15 m, 0.30 m	27°	0.51
	Average, Age > 50	*Down*	*0.18 m, 0.29 m*	*32°*	*0.65*
			0.15 m, 0.30 m	*27°*	*0.66*
		Up	*0.18 m, 0.29 m*	*32°*	*0.50*
			0.15 m, 0.30 m	*27°*	*0.47*
	Overall Average	***Down***	***0.18 m, 0.29 m***	***32°***	***0.79***
			0.15 m, 0.30 m	***27°***	***0.86***
		Up	***0.18 m, 0.29 m***	***32°***	***0.60***
			0.15 m, 0.30 m	***27°***	***0.64***

Table D2 : Free-flow Speed for Stairs (Various sources)

Author	Year	Sample Type/Infrastructure Type	Direction	Mean Speed (m/s)	Standard Deviation (m/s)
Hankin & Wright	1958	Unimpeded passenger flows in subways.	Up	0.8*	
			Down	0.98*	
ITE	1976	Riser height has significant impact on speed.	Up	0.5 horz. speed	
			Down	0.6 horz. speed	
Jordaan	1981	Design value only.	Average	0.65 m/s*	
Fruin (summary of previous table D1, but here represented as horz. speeds)	1987	Commuter Movement, Normal stair locomotion (n = 700) Gradient : 32°	Down	0.67	
		Gradient : 27°	Down	0.78	
		Gradient : 32°	Up	0.51	
		Gradient : 27°	Up	0.57	
Weidmann	1993	An average of 58 individual studies.	Up	0.610 (horz. speed)	Range (0.391 to 1.16)
Pauls in SFPE handbook	1995	Observations of high-rise building evacuation drills. (Optimal flow conditions)	Down	0.52	
SFPE handbook	1995	Average	Down	0.9 (0.8 horz. speed)	
Cheung & Lam	1998	Six stations in Hong Kong (n = 696).	Up	0.86	95%tile confidence range: (0.84 to 0.88)
		Six stations in Hong Kong (n = 687).	Down	0.97	95%tile confidence range: (0.96 to 0.98)
Lam & Cheung	2000	MTR and KCR stations in Hong Kong (n < 696).	Up	0.77 – 0.86	
			Down	0.87 – 0.97	
Xiang *et al.*	2003	Singapore MRT Station (n = 559); average speed.	Down	0.453*	
Fujiyama & Tyler	2004	Students and staff of University College, London . Young (30-50) 38.8°	Up	Male: 0.50, Female:0.47	
		Elderly (>50) 38.8°	Up	Male: 0.41, Female: 0.46	
		Young (30-50) 35°	Up	Male: 0.57, Female: 0.56	
		Elderly (>50) 35°	Up	Male: 0.50, Female: 0.53	
		Young (30-50) 30,5°	Up	Male: 0.65, Female: 0.62	
		Elderly (>50) 30,5°	Up	Male: 0.56, Female: 0.60	
		Young (30-50) 24.6°	Up	Male: 0.77, Female: 0.75	
		Elderly (>50) 24.6°	Up	Male: 0.68, Female: 0.76	
		Students and staff of University College, London . Young (30-50) 38.8°	Down	Male: 0.61, Female: 0.57	
		Elderly (>50) 38.8°	Down	Male: 0.46, Female: 0.48	
		Young (30-50) 35°	Down	Male: 0.62, Female :0.67	
		Elderly (>50) 35°	Down	Male: 0.60, Female: 0.57	
		Young (30-50) 30,5°	Down	Male: 0.72, Female: 0.76	
		Elderly (>50) 30,5°	Down	Male: 0.64, Female :0.64	
		Young (30-50) 24.6°	Down	Male: 0.82, Female: 0.91	
		Elderly (>50) 24.6°	Down	Male: 0.80, Female: 0.80	
Daamen & Hoogendoorn	2004	Holland, Delft Station.	Up	0.70*	0.06
			Down	0.75*	0.16
Berrou *et al.*	2005	London commuter (n = 1500)	Up	0.74 (horz. speed)	0.24
		Hong Kong commuter (n = 705)	Down	0.71 (horz. speed)	0.22
Brocklehurst – Paper 4	2005b	Deacons Secondary School, Petersborough (UK)	Up	0.85*	0.23
			Down	0.96*	0.24
Kretz *et al.* (long Stair)	2008	Dutch Pavilion at the Expo 2000 in Hannover, Germany Category A: unimpeded (n = 73)	Ave. of up and down	0.423 (horz. speed)	0.130
		Category B : Slightly impeded (n = 390)	Ave. of up and down	0.382 (horz. speed)	0.075
		Category C : High Density (n = 23)	Ave. of up and down	0.359 (horz .speed)	0.040
Kretz *et al.* (short stair)	2008	World Team Cup tennis tournament 2004, Düsseldorf.	Up	0.71 (horz. speed)	Range (0.13 – 1.86)
			Down	0.65 (horz. speed)	Range (0.21 – 1.39)
CIBSE Guide D	2008	Young middle aged men (Free flow design density).	Not indicated (general movement)	0.9 (q = 27 pax/m) slope @ 0.6 pax/m^2 density	
		Young middle aged women.		0.7 (q = 21 pax/m) slope @ 0.6 pax/m^2 density	
		Elderly people, groups.		0.5 (q = 15 pax/m) slope @ 0.6 pax/m^2 density	
Ye *et al.*	2008	Metro station in Shanghai, China (n = 410)	Down	> 0.92*	
		Metro station in Shanghai, China (n = 346)	Up	> 0.75*	

**Slope or horizontal speed not defined*

Table D3 : Stair Capacity Values (Various sources)

Author	Year	Location	Sample Type/Details	Capacity Density (pax/m^2)	Capacity Flow Rate (pax/min/m)	Critical Speed (m/s)
Hankin & Wright	1958	Uni-directional flow, measured between hand-rails. Subtract 300 mm from a 1.0 m wide route to obtain effective width.	Down direction		69 (79.8 if over effective width)	
			Up direction		62	
Oeding	1963	Heavy queuing conditions	Observed maximum flow rate.		55 (79 if over effective width)	
Predtechenskii & Milinskii	1969		Observed peak capacities.	3.5		
SCICON	1972	Football and Rugby stadia	Maximum capacity observed over a short peak period. Not considered sustainable.		82	
Pushkarev & Zupan	1975	Subway stairs	Uni-directional flow up stairs		42 - 53	
Johnson	1979	Building Practice Code – <u>Design guideline</u> for design of stair width only.	Average (for both ascending and descending direction)		40 - 50	
Pauls in SFPE handbook	1980, 1995	Multi-Storey buildings (Result of 58 experiments)	Mean maximum flow rate. Speed at crush conditions.		78	0.22
			Range of values		43 - 71	
Green Guide (Home Office *et al.* 1985),	1985		Recommended maximum <u>design</u> flow rate for stepped routes.		73	
Fruin	1987	Fruin observed max flow rates at a density of 3 ft^2/pax (n = 700)	Down direction	± 3.59	68.6	
			Up direction	± 3.59	62.0	
Daly *et al.*	1991	London Underground	Up direction		62	0.36
			Down direction		68.3	0.56
SFPE handbook	1995		Optimum density at stair capacity.	1.9		
			Riser = 191 mm, tread = 254 mm		56	
			Riser = 178 mm, tread = 279 mm		61	
			Riser = 165 mm, tread = 305 mm		65	
			Riser = 165 mm, tread = 330 mm		70	
Cheung & Lam	1998	Six selected stations in Hong Kong (tread = 305 mm and riser = 150 mm)	Up direction		70	0.43
			Down direction		80	0.60
Lam & Cheung	2000	MTR and KCR railway stations in Hong Kong.	Up direction		70	0.42 - 0.43
			Down direction		73 - 80	0.57 - 0.60
British Standards Institute (BSI)	2000	European Standards, Spectator Facilities.	Guidance Value from unknown origin		66	
Xiang *et al.*	2003	Singapore MRT Station (n = 559)	Down direction only		80	
NFPA 130	2003	Stairs, stopped escalators and ramps < 4% slope.	Evacuation <u>design</u> guideline : Up direction		62.6	
			Evacuation <u>design</u> guideline : Down direction		71.7	
Lee & Lam	2003	Mongkok MTR Station, Hong Kong.	Up: (n = 6244) at r = 1.0 & (r = 0.1)		67 (53)	0.56 (0.42)* (horz. likely)
			Down: (n = 8642) at r = 1.0 & (r = 0.1)		78 (60)	0.65 (0.48)* (horz. likely)
Galea *et al.*	2004	Airplane evacuation experiments using VLES simulator.	Downwards direction	2.5 to 3.5	79.8	
			Upwards direction	5.0	110.1	
Brocklehurst *et al.* Brocklehurst (2005c)	2004	Deductions from SCICON.	A more appropriate 2 – 3 min flow rate. See SCICON flow capacity above.		62 - 75 (68 average)	
Brocklehurst *et al.*	2004/ 2005	Stair flow rate measured at crowded conditions at Ascot Racecourse.	Person/s maintain density LOS levels.		45	
			For low Incline stepped gangways.		45 - 55	
LUL	2005	Escape capacity <u>guidelines</u> for London Underground.	Horizontal Circulation (Stairs and stopped escalators)		56	
Brocklehurst *et al.*	2005	Deacons Secondary School, Petersborough (UK).	Predominantly downwards flow direction with little counterflow.		76	
Hostikka *et al.*	2007	Helsinki University of Technology (HUT) main library.	Controlled evacuation experiment – down stairs (2nd to 4th floors).		48 - 49.2	0.76 - 1.30 (slope)
UK Building Code					80	
Galea *et al.*	2008	Trade Centre Towers, New York (Evacuation of 14,000 people in 2001 terrorist 911 attack).	Excludes those with disabilities or other reported reasons for travelling slow.			0.33
CIBSE Guide D	2008	Guideline document (Full flow <u>design</u> density).	Young middle aged men & women	2.0	60	0.6 (slope)
			Elderly people, groups	2.0	40	0.4 (slope)
Ye *et al.*	2008	Metro station in Shanghai, China	n = 410, down	> 1.7	74.4	< 0.58*
		Metro station in Shanghai, China	n = 346, up	> 2.7	60.6	< 0.35 *

Table D4 : Capacity Values on Level Ground (Various Sources)

Author	Year	Location	Sample Type/Details	Jam Density (pax/m²)	Capacity Density (pax/m²)	Capacity Flow Rate (pax/m/min)	Speed at Capacity Flow Rate (m/s)
Hankin & Wright	1958	Flows in Subways	Max flow proportional at widths > 1.2 m		1.4	89	
		Boy School	Max measured fully loaded flow rate.			100	
		Peak flow observed under rare and instantaneous conditions.				115.2	
Turner	1959	Fully loaded rail stations			1.4	89	1.06
Oeding	1963	Germany	Mixed Traffic	3.98		89.4	
Older	1968	Oxford Street pavements (London, UK) – shoppers, mixed (unknown age)		3.7		78	
Navin & Wheeler	1969	United States		3.9		64	
Predtechenskii & Miliniskii	1969	Russia	Peak flows at high density for adults in summer dress.			123.6	
Fruin	1971	Max flow is ultimate regimented, "*funnelled*" flow under pressure		3.8		81	
O'Flaherty *et al.*	1972				1.89	75.6	0.68
SCICON	1972	Football stadia gateway	Average flow rate over 3 minutes. Value in brackets is the peak flow rate			98 (115)	
		Football stadia passageway (passageway > 3.05m long)	Average flow rate over 3 minutes. Value in brackets is the peak flow rate .			75 (82)	
Pushkarev & Zupan	1975			2.5 – 5.0	2.1	100.2	1.11
Polus *et al.*	1983	Israel	Walkways and sports stadia			94.8	
Tanaboriboon *et al.*	1986	Singapore sidewalks		4.83		89.24	
Fruin	1987	Walkways	Uni-directional commuter flow	3.99	2.2	86	
Pauls	1987			4.0 – 5.0			
Ando *et al.*	1988	Fully loaded rail stations	Japanese persons		4.5	101 - 108	0.37
SABS	1990	Evacuation guidelines				105 – 109	
Tanaboriboon & Guyano	1991	Bangkok, Thailand	Mixed Traffic	5.55		101.05	
Daly *et al.*	1991	Fully loaded rail stations	Fully loaded station passageway		1.4	86	0.6
Yu	1993	Shanghai, China	Mixed Traffic	5.1		95.97	
Weidmann	1993			> 5.4	1.75	73.8	0.7
AASHTO	1994	Walkway capacity guideline	Street walkways only			80	
Virkler & Elayadath	1994				1.3 – 1.8	61.8 – 72.0	0.75 – 0.82
Sarkar & Janardhan	1997			> 4.2	2.1	91.8	0.74
Green Guide - derived from SCICON (1972)	1997		To be used with caution. Appears unachievable according to Brocklehurst.			109	
Primrose Guide (Home Office *et al.)*	1998		Step wise relationship based on unit width = 0.525 m			40 pax/m/ unit exit width	
Lam & Cheung	2000	MTR and KCR Stations in Hong Kong	Passageway			88-92	0.6 – 0.61
HCM	2000	Guidelines for walkway capacities			1.33	75	0.75
British Standards Institute (BSI)	2000	Football gateways/portals	European Standard Spectator Facilities; Part 1			83	
AlGadhi *et al.*	2001	Saudi Arabia, Makkah	Yearly stone throwing ritual by pilgrims	7.0			
NFPA 130	2003	Platforms, corridors and ramps of < 4% slope	Evacuation design standard			89.4	
LUL	2005	Escape capacity guidelines for London Underground	Horizontal Circulation (Passageways)			80	
Brocklehurst *et al.*	2005a	Ascot vomitory over 8.6 m width.	Forced flow, *n* = 23		2.69	42	0.26
			Corridor capacity flow rates for min 1.31 m corridor width.			97	
			Unforced flow			25.6 – 30.2	
Brocklehurst *et al.*	2005b	Deacons Secondary school, Petersborough (UK)	Average door flow rates (0.8 m wide door)			48	
Lee & Lam	2005	Causeway Bay MTR Station, Hong Kong	Walkway leading to escalator (*n* = 1,232)			120	0.31
Hostikka *et al.*	2007	Helsinki University of Technology (HUT) main library.	Controlled evacuation experiment conducted on a smooth floor.			75.6	
Ye *et al.*	2008	Metro station in Shanghai, China (*n* = 714)	One-way Passageway		1.7	82.8	0.75
		Metro station in Shanghai, China (*n* = 619)	Two-way Passageway		> 1.2	71.4	< 0.82
Saif	2009	Khalid Bin Alwaleed Road, Makkah, Saudi Arabia	Worshippers walking to the Holy Mosque	3.1		51	

Table D5 : Free-flow Walking Speed for Level Ground (Various sources)

Author	Year	Location	Sample type/mix	Free Speed space-density (m^2/pax)	Mean Free Speed (m/s)	Std. deviation (m/s)	Flow Rate (pax/m/min)
Peschel	1957	Pedestrian crossing	Mix of men & women, 6 -10 years old		1.1		
			Mix of men & women, 13 -19 years old		1.8		
			Men < 40 years old		1.7		
			Men > 55 years old		1.5		
Hankin & Wright	1958	Subways (United Kingdom)	Mix (unknown age)		1.6		88.8
Turner	1959	Fully loaded rail stations			1.6		
Oeding	1963	Germany	Mixed traffic		1.5		
Older	1968	Oxford Street pavements (London, UK) - shoppers	Mixed (unknown age)		1.0 – 1.4 (1.32)	0.3	
Hoel	1968	United States	CBD		1.5	0.2	
Navin & Wheeler	1969	United States			1.32		
Predtechenskii & Miliniskii	1969	Russia	Design Flow				102.0
ITE	1969	United States			1.2		
Fruin	1971	United States		< 2.0	1.35	0.15	82.2
Surti & Burke	1971	Tourists outside Whitehouse in Washington.	Average walking speed of tourists.		1.0		
			Average walking speed of "*other*" pedestrians		1.6		
Henderson	1971	Pedestrian crossing	Men (unknown age)		1.6	0.2	
			Women (unknown age)		1.4	0.2	
		Students on a Campus sidewalk.	Men (unknown age)		1.6	0.2	
			Women (unknown age)		1.5	0.1	
		Average - Australia			1.44	0.23	
O'Flaherty & Parkinson	1972	United Kingdom		< 1.67	1.32	1	
SCICON	1972	United Kingdom	Data from football crowds.		1.37		82.2
Sleight	1972	United States			1.37		
Hulbert	1976	United States	Average walking speed.		1.3 - 1.4		
Tregenza	1976	United Kingdom			1.31	0.3	
Kamino	1980	Paris, France			1.46		
		Fukuoka, Japan			1.35		
		Tokyo, Japan			1.56		
		Osaka, Japan			1.50		
		Koori-cho, Fukushima, Japan			1.16		
Jordaan	1981	South Africa	Design value only		1.0		
Roddin	1981	United States			1.6		
Polus *et al.*	1983	City streets of Haifa	Men (unknown age)		1.3	0.3	94.8
			Women (unknown age)		1.1	0.3	75
Jordaan & Joubert	1983	South Africa	Average		1.44		
			Children		1.6		
			Older People		1.3		
AASHTO	1984	United States			1.3 - 1.4		
Tanaboriboon *et al.*	1986	Singapore Sidewalks	Average (n = 519)		1.23	0.20	
Fruin	1987	Commuter movement around the Port Authority Bus Terminal / Pennsylvania Station (NYC)	Men (unknown age)	2.5	1.4		
			Women (unknown age)	2.5	1.3		
			Average (n = 1,000)		1.35		

Table D5 : Free-flow Walking Speed for Level Ground (Various sources)

Author	Year	Location	Sample type/mix	Free Speed space-density (m^2/pax)	Mean Free Speed (m/s)	Std. deviation (m/s)	Flow Rate (pax/m/min)
Pauls	1987	United States		< 2.0	1.25		
Davis *et al.*	1988	Mirabel, Ottawa and Pearson Airports, Canada	Average free flow speed of baggage laden and un-laden pedestrians. (Sample *n* = 733)		1.55		
Koushki	1988	Saudi-Arabia			1.08		
FHWA	1988	United States			1.2		
Ando *et al.*	1988	Fully loaded railway stations.	Japanese persons		1.4		
HMSO (Guide to Safety at Sports Grounds)	1990	Data derived from 1.0 persons per 0.55 m/s unit exit width calculation.	Japanese data				109.2
HMSO (Approved Document B1)	1991	Standard British code for Buildings.					80.0
Tanaboriboon & Guyano	1991	Thailand			1.22		
Daly *et al.*	1991	United Kingdom			1.47		85.8
Morrall *et al.*	1991	Canada			1.4		
		Sri Lanka			1.25		
Coffin	1993	Calgary, Canada	Elderly (> 60 yrs) pedestrians at signalised intersections. Proposed design speed.		1.20		
			Elderly (> 60 yrs) pedestrians at unsignalised midblock crossing. Proposed design speed.		1.00		
Weidmann	1993	Germany, Walkways		< 2.0	1.34	0.26	
Yu	1993	Shanghai, China	Mixed Traffic		1.26		
Virkler & Elayadath	1994	United States			1.22		
Gerilla	1995	Metro Manila, Philippines	Mixed Traffic		1.18		
Knoflacher	1995	Austria			1.45		
Lam *et al.*	1995	Hong Kong			1.19	0.26	
Knoblauch *et al.*	1996	Washington, Baltimore, Maryland, New York (USA)	Crosswalks alongside roadway , Age > 65)		1.25		
			Younger pedestrians < 65 years		1.51		
			Males > 65 years		1.31		
			Males < 65 years		1.56		
			Females > 65 years		1.19		
			Females < 65 years		1.46		
Sarkar & Janardhan	1997	India			1.46	0.63	
CROW	1998	The Netherlands			1.4		
Young	1998	United States			1.38	0.27	
Still	2000	Wembley Stadium, London, UK			1.34	0.26	
Lam & Cheung	2000	MTR and KCR Stations in Hong Kong	Entire population - passageway		1.32 – 1.37		
			Concourse (straight movement)		1.28 – 1.29		
			Concourse (turning movement)		1.28 – 1.30		
			Platform		1.24 – 1.27		
Still	2000	Towards the entrances at Happy Valley and Sha Tin Racecourses	Mixed (unknown age)		1.2		
HCM	2000	Guidelines for crosswalk walking speeds (Note, that the current 1998 HCM used a 1.4 m/s design speed)	< 20% population over 65 years old		1.2		
			>20% population over 65 years old		1.0		
Bennett *et al.*	2001	Street intersection signalised crossings (Glen Waverley, Camberwell and Balwyn) in Melbourne, Australia.	Pedestrians with walking difficulty		1.35	0.25	
			Pedestrians without walking difficulty		1.70	0.50	
			All pedestrians		1.63	0.48	
Helbing *et al.*	2001	Unknown	Unknown		1.3	0.3	
IMO	2002	Passenger Ships	Maximum design flow rate (for evacuation)				80.0

Table D5 : Free-flow Walking Speed for Level Ground (Various sources)

Author	Year	Location	Sample type/mix	Free Speed space-density (m^2/pax)	Mean Free Speed (m/s)	Std. deviation (m/s)	Flow Rate (pax/m/min)
Teknomo	2002	Road intersection crossing in Sendai, Japan	All crossing pedestrians in measurement area.		1.38	0.37	
Klüpfel *et al.*	2003	Hannover, Germany	World Exhibition Centre		1.30	0.21	
NFPA 101	2003	United States	Design flow rate. Comment: effectively same as UK codes				80.0
Willis *et al.*	2004	Street sidewalks in Edinburgh and York, UK (*n* = 2,613)	Whole sample (min = 0.45, max = 5.56)		1.47	0.299	
			Males only		1.52	0.333	
			Females only		1.42	0.251	
Daamen & Hoogendoorn	2004	Holland, Delft Railway Station (Platform observations)	Alighting Passengers		1.35	0.11	
			Boarding Passengers		0.97	0.11	
Daamen	2004	Holland, Delft University campus*	60 subjects equally distributed over age & gender		1.406	0.213	0.733Pax/m per layer
			Equal bi-directional		1.296	0.206	
			Wide bottleneck		1.239	0.282	0.776Pax/m per layer
			Narrow bottleneck (4.0 m wide)		0.815	0.405	0.78Pax/m per layer
			Platform: alighting train		1.35	0.11	
			Platform: boarding train		0.99	0.11	
Berrou *et al.*	2005	New York Grand Central	Commuters (*n* = 4,762)		1.50	0.21	
		London Clapham Junction	Commuters (*n* = 1,043)		1.55	0.23	
		Hong Kong Port (open air)	Commuters (*n* = 588)		1.47	0.21	
		Hong Kong Tsim Tsa Tsui	Commuters (*n* = 485)		1.32	0.22	
			Week Enders (*n* = 1,560)		1.25	0.22	
		Monaco Train Station	Commuters (*n* = 2,524)		1.40	0.19	
		Leeds Outside Stadium	Football Egress (*n* = 6,777)		1.43	0.20	
Brocklehurst *et al.*	2005a	Pedestrian path from train station to Ascot Racecourse	Men (unknown age)		1.51		
			Women (unknown age)		1.26		
			Groups of men and women together		1.3		
		Ascot Vomitory	Un-forced flow regime. A total of 23 measurements were taken over 8.6 m width.	2.16			52
Brocklehurst *et al.*	2005b	Deacons Secondary school, Peterborough (UK)	Average Corridor free-speeds for secondary school children		1.25	0.13	
NYC DCP	2006	New York City, USA	All pedestrians: (*n* = 8,871)		1.30		
			Males: (*n* = 4,876)		1.35		
			Females: (*n* = 3,995)		1.25		
Finnis & Walton	2007	Auckland, Wellington (New Zealand)	Flat locations: (*n* = 1,071)		1.47	0.23	
			Commuters at a train station (*n* = 519)		1.57	0.17	
CIBSE Guide D	2008	Corridor design guideline document only (not empirical)	Commuters only (k = 1.4 pax/m^2)	0.71	1.0		84
			Commuters only (k = 0.3 pax/m^2)	3.33	1.5		27
Ye *et al.*	2008	Metro station in Shanghai, China	All population: (*n* = 714)		>1.2		
		Metro station in Shanghai, China	All population: (*n* = 619)		>1.2		
Saif	2009	Khalid Bin Alwaleed Road, Makkah, Saudi Arabia	Worshippers walking to the Holy Mosque		1.09		
Matsumoto *et al.*	2010	Shibuya street crossing close to railway station, Tokyo, Japan	Pram users: (*n* = 229) Persons hurrying: (*n* = 150) Persons walking in groups: (*n* = 237) Normal person sample		1.15 2.70 1,26 1.85	0.3 0.75 0.20 0.25	

**Note that only those pedestrians being good walkers might have subscribed to the experiment*

Table D6 : Bottleneck data

Author	Year	Observation or Simulation	Sample type/mix	Bottleneck Width (m)	Max Flow Rate (pax/m)
Thompson	2004	Simulation (using SIMULEX)	Passenger ship population. Results of bottleneck experiment. Data not compared to real life data.	0.8	20
				0.9	44
				1.1	88

Table D7 : Turnstile/Access Gate Capacities (Various sources)

Author	Year	Location	Turnstile Type	Capacity flow rate per turnstile (pax/min)
Jordaan	1981	Design volume only	Ticket gate (not specified, but likely to be cattlegrid type turnstile)	45
TRB	1999c	Observed average fare gate capacities.	Free admission (barrier only)	40 – 60
			Ticket collection by staff	25 – 35
			Card reader (various types)	25 – 40
			High entrance/exit turnstile	20
			High exit turnstile	28
			Exit gate (0.9 m wide)	75
			Exit gate (1.2 m wide)	100
			Exit gate (1.5 m wide)	125
NFPA 130	2003	Evacuation design guideline only	Doors and gates (minimum 914.4 mm wide)	89.4
			Clear unobstructed 508 mm wide fare gate	50
			Turnstile type free wheel in exit direction	25
Brocklehurst *et al.*	2003	Ascot Racecourse (UK)	Mixed flow, 50% women with 60% > 35 years old.	11
Hoogendoorn *et al.*	2004	None	Magnetic system, where passengers insert a magnetic card.	25
		None	Contactless System, scans if a passengers has a valid card or not.	40
LUL	2005	Escape capacity guideline for London Underground	Unobstructed Ticket System (UTS)	50
Illiso *et al.*	2007	Design Report (Moses Mabhida station)	Average turnstile flow rate	30
Arcus Gibb	2008c	Design Report (Cape Town station)	Average turnstile flow rate	33
CIBSE Guide D	2008	Guideline document	Revolving door	25 – 35
			Free admission	40 – 60
			Cashier	12 – 18
			Single coin operation	25 – 50
			Card/detector operation	20 – 30
			Swing door (1m wide)	40 – 60
			Clear opening of 1m wide	60 – 110
SARCC	2008b	Technical Specification	High Speed Access Gate system (HSAG), Gates are to be bi-directional.	60
Hermant survey (4/12/2009)	2009	Bonteheuwel Station	Cattle grid, manual checking system, AM Peak (exit flows).	45 – 55
De Gersigny survey (15/12/2009)	2009	Cape Town Station (07:30 – 07:45)	Turnstiles (automatically revolving gates) – this means that 35 pax/min is the max due to motorised gates. AM Peak (exit flows)	34 – 35

Table D8 : Boarding and Alighting Data (Various sources)

Author	Year	Location	Population Type	Mean Boarding and Alighting (sec/pax)
Daamen & Hoogendoorn	2003	11 Dutch railway stations.	General	1.0
Rindsfüser & Klügl	2007	Bern railway station.	General (model assumption). Simulation only, not empirical.	1.0
Daamen *et al.*	2008	Controlled (in-laboratory) experiments.	Capacity dependant on gap width, height, luggage (door opening constant at 80 cm in this case).	1.1 to 1.79
Zhang *et al.*	2008	Observations at Beijing, China metro stations.	General. Capacity dependant on ratio of boarding to alighting group size.	0.5 to 2.5

15. APPENDIX E: DATA COLLECTION AND PROCESSING

Data Recording Method:

In the research undertaken for this dissertation, MiniDV camera devices, or mini digital-video devices were used to film the pedestrian surveys. These devices record footage onto small cassette tapes. The device can be linked to a personal computer using an IEEE 1394 (Fire Wire/I-link) DV interface. Data from the video camera recorders were transferred directly to a laptop using *Windows Movie Maker*™ (version 5.1) software providing a 25 fps video frame rate at a 720 (width) x 576 (height) pixel frame size saved as a Windows Media Video "*.wmv*" format. One hour of raw (high definition) footage consumed approximately 13,2 Gb of data storage space. The file codec[8] was however incompatible with the customised "*Headrecorder*" software programme and needed to be converted to a "*xvid*" codec Audio Video Interleave or "*.avi*" file using the "*Any Video Converter Version 2.7.6"*™ application software.

Data Collection Parameters:

The suite of observations considered to be conducted (listed from most important to least important) are briefly listed as follows (and described in further detail thereunder):

- Walking speeds (on level and on stair terrain) leading to macroscopic flow characteristics,
- Coach boarding and alighting rates,
- Passenger arrival rates,
- Walking behaviour and
- Route choice,

Walking speeds on level terrain and stairs leading to macroscopic flow characteristics.

Individual pedestrian trajectories, space mean speeds (SMS), densities (k), flows (q), captured according to gender, person size, group size, effect of baggage and trip purpose characteristics formed part of the primary research requirements of the study. Observations of pedestrian traffic for different station infrastructure components (e.g. platforms, wide and narrow staircases and skywalks during different times of the day were also undertaken to determine macroscopic relationships.

Coach boarding and alighting characteristics

This included identifying the rate at which passengers boarded or alighted, duration of the overall boarding and alighting processes and total dwell time. B&A observation is a relatively new research direction with only a few researchers being involved with boarding and alighting quantitative observations internationally including Wiggenraad (2001); Daamen and Hoogendoorn (2003a); Zhang *et al.* (2008) and Daamen *et al.* (2008). The B&A observations conducted in this study at the local survey stations were not part of the planned primary survey objectives, but rather an opportunistic secondary objective that presented itself and that was assessed to compare the B&A rates with international findings. The results will nevertheless be utilised in the calibration of the SP-model.

Passenger Arrival Rate (*PAR*)

The passenger arrival rate (*PAR*) is necessary to develop the longitudinal passenger arrival profile, in other words, this parameter attempts to identify whether commuters arrive uniformly or according to some other distribution pattern prior to train departures or whether the arrival rate is purely random.

Walking behaviour

Walking behaviour could be observed from the video recordings but these would be primarily qualitative observations, e.g. observing inter-person space requirements, gait hesitancy prior to negotiating stairs, usage of stair handrails, usage of skywalk handrails etc. Although useful, this dataset was not considered in this research, as it would not significantly contribute to the development of the first version of the SP-model.

Route choice.

Although this may be applicable in larger stations with route choice options, this attribute was not considered in this research. This is because the stations where surveys were conducted, and the SP-model, only allow for a single route choice until the foyer after which two route choices are available, which are entirely dependent on the origin/destination of the pedestrian, rather than influenced by en-route pedestrian dynamics and obstacles.

Survey Details and Sample Rates:

Table E1 shows the detailed breakdown of all the surveys performed over the two-month period. Tape 1, from the pilot study and was divided into three parts viz. a, b and c of which only the latter two were considered for data collection purposes. Sample sizes shown in the table indicate the total raw sample size and also indicates data items that have been rejected for whatever reason.

Note that sample sizes listed in Table E1 include the MFD, Dwell and B&A datasets. The MFD sample refers to the number of pedestrians tracked for the purposes of determining the macroscopic fundamental diagram (MFD). The dwell sample refers to the number of occurrences on the particular tape where trains stopped and their dwell times could be recorded. Additional train dwell times were also recorded manually for all platforms during the recording process.

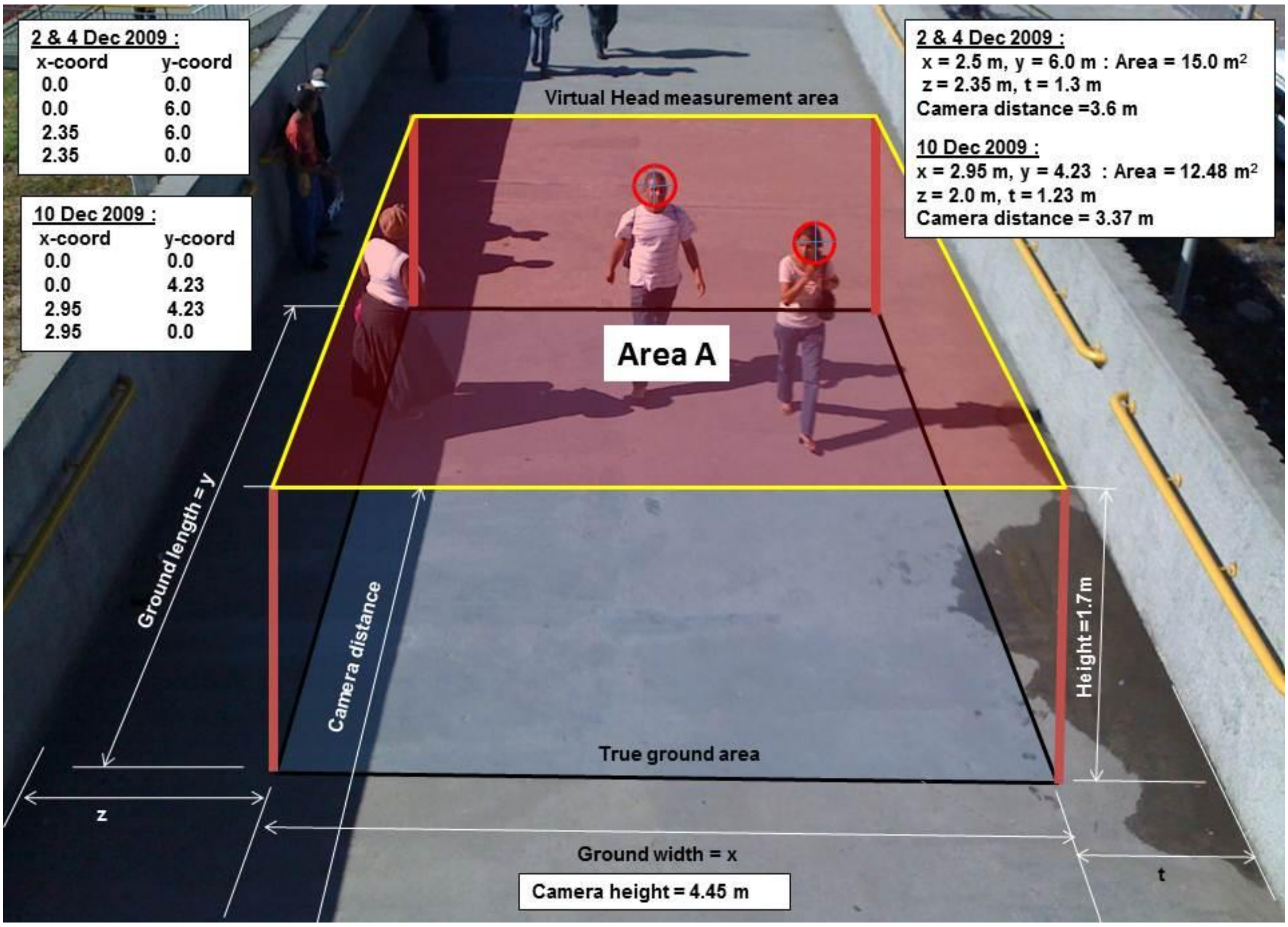
Table E1: Details of surveys and sample rates achieved

Tape	Time	Date	Infrastructure	Station	Sample size (*n*)	
					MFD	**B&A / Dwell**
1b	AM	2 Dec 2009	Narrow stairs	B/heuwel	DNC	-
1c	PM	2 Dec 2009	Platform	B/heuwel	93	-
2	PM	2 Dec 2009	Skywalk	B/heuwel	1,245	-
3	PM	3 Dec 2009	Wide stairs	B/heuwel	DNC	-
4	PM	3 Dec 2009	Platform	B/heuwel	819	-
5	AM	4 Dec 2009	Skywalk	B/heuwel	1,610	-
6	AM	4 Dec 2009	Platform	B/heuwel	527	-
7	PM	8 Dec 2009	Narrow stairs	B/heuwel	DNC	-
8	PM	8 Dec 2009	Wide stairs	B/heuwel	DNC	-
9	AM	9 Dec 2009	Narrow stairs	B/heuwel	DNC	2
10	AM	9 Dec 2009	Wide stairs	B/heuwel	DNC	6
11	AM	9 Dec 2009	Platform 3 East (B&A)	B/heuwel	-	12
12	PM	9 Dec 2009	Skywalk	Maitland	1,129	-
13	PM	9 Dec 2009	South Skywalk	Maitland	784	-
14	PM	9 Dec 2009	Platform	Maitland	SUN	-
15	AM	10 Dec 2009	Skywalk	Maitland	2,214	-
16	AM	10 Dec 2009	Platform	Maitland	486	-
17	AM	10 Dec 2009	Platform 4 (B&A)	Maitland	-	8
18	PM	10 Dec 2009	Skywalk	B/heuwel	2,290	-
19	PM	10 Dec 2009	Narrow stairs	B/heuwel	DNC	5
20	PM	10 Dec 2009	Wide stairs	B/heuwel	DNC	1
21	AM	11 Dec 2009	Skywalk	Maitland	2,945	-
22	AM	11 Dec 2009	Platform	Maitland	541	-
23	AM	11 Dec 2009	Various Platforms (B&A)	Maitland	-	15
24	AM	1 Feb 2010	Platform 3 West (B&A)	B/heuwel	-	19
25	AM	1 Feb 2010	Platform 3 East (B&A)	B/heuwel	-	20
26	AM	2 Feb 2010	Platform	B/heuwel	470	-
27	AM	2 Feb 2010	Narrow stairs	B/heuwel	1,079	6
28	PM	2 Feb 2010	Platform	B/heuwel	519	6
29	PM	2 Feb 2010	Narrow stairs	B/heuwel	1,356	-
30	AM	3 Feb 2010	Platform 3 East (B&A)	B/heuwel	-	10
31	AM	3 Feb 2010	Narrow stairs	B/heuwel	878	-
32	PM	3 Feb 2010	Narrow stairs	B/heuwel	1,595	-
33	PM	3 Feb 2010	Platform 2 East (B&A)	B/heuwel	-	10
34	AM	4 Feb 2010	Wide stairs	B/heuwel	1,817	6
35	AM	4 Feb 2010	Platform 3 East (B&A)	B/heuwel	-	15
36	PM	4 Feb 2010	Wide stairs	B/heuwel	1,846	-
37	PM	4 Feb 2010	Platform 4 East (B&A)	B/heuwel	-	9
38	AM	5 Feb 2010	Wide stairs	B/heuwel	DNC	15
39	AM	5 Feb 2010	Platform 3 East (B&A)	B/heuwel	-	8
40	AM	9 Feb 2010	Narrow stairs	B/heuwel	949	7
41	AM	9 Feb 2010	Platform 3 East (B&A)	B/heuwel	-	11
42	PM	9 Feb 2010	Wide stairs	B/heuwel	DNC	3
43	PM	9 Feb 2010	Platform 4 West (B&A)	B/heuwel	-	9

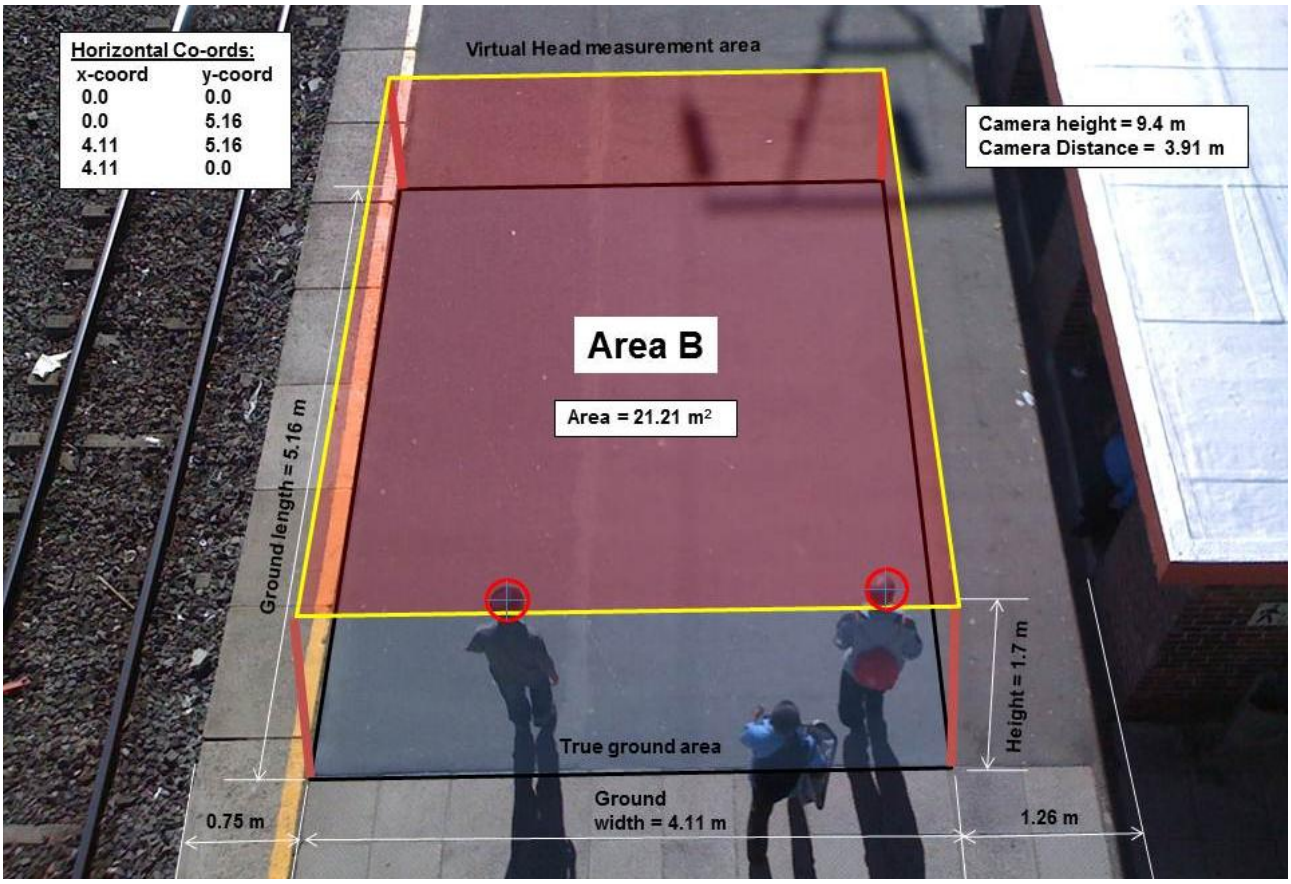
SUN: Data not considered due to intense sun reflection on clothing making it difficult to track pedestrians.

DNC: Data not considered due to > 8% MAL error or other problems.

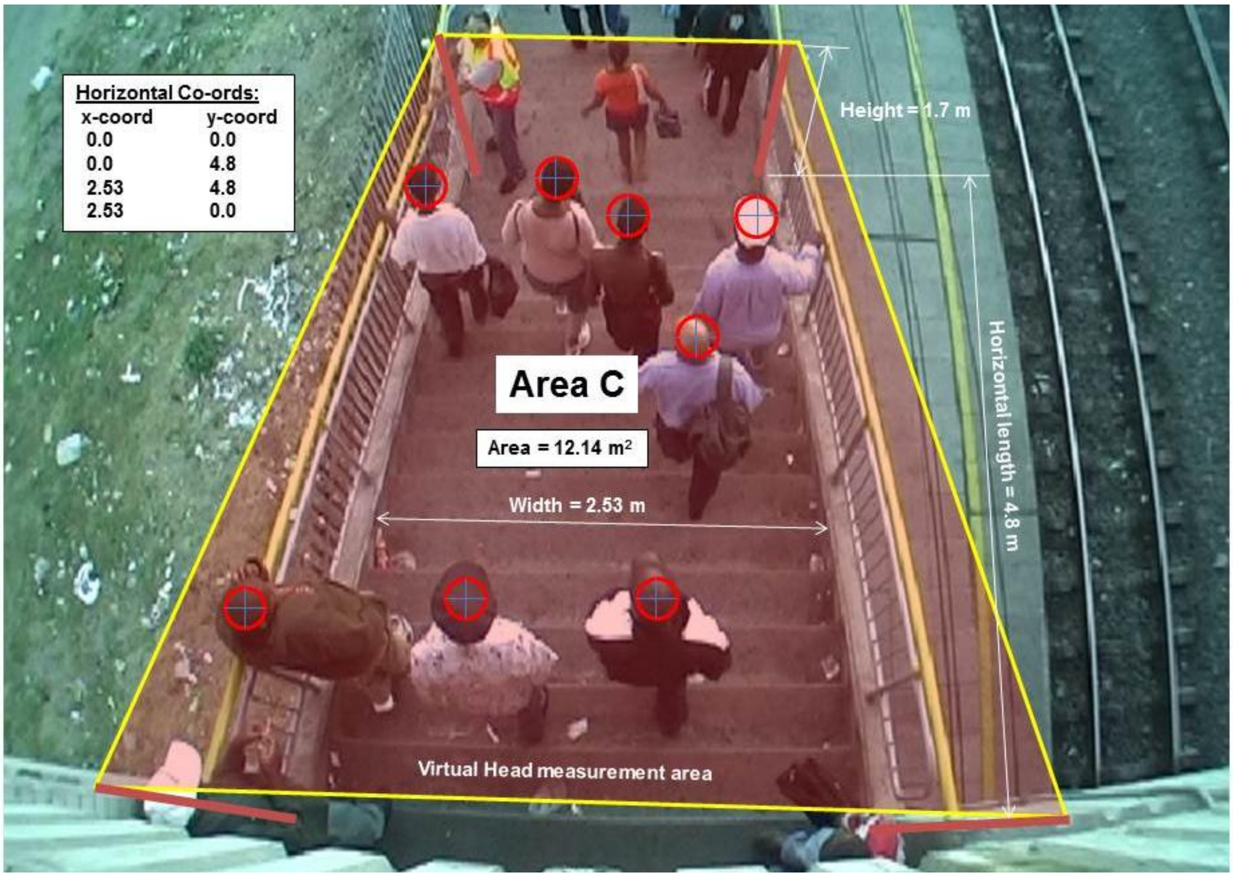
16. APPENDIX F: GEOMETRIC DETAILS OF MEASUREMENT AREAS



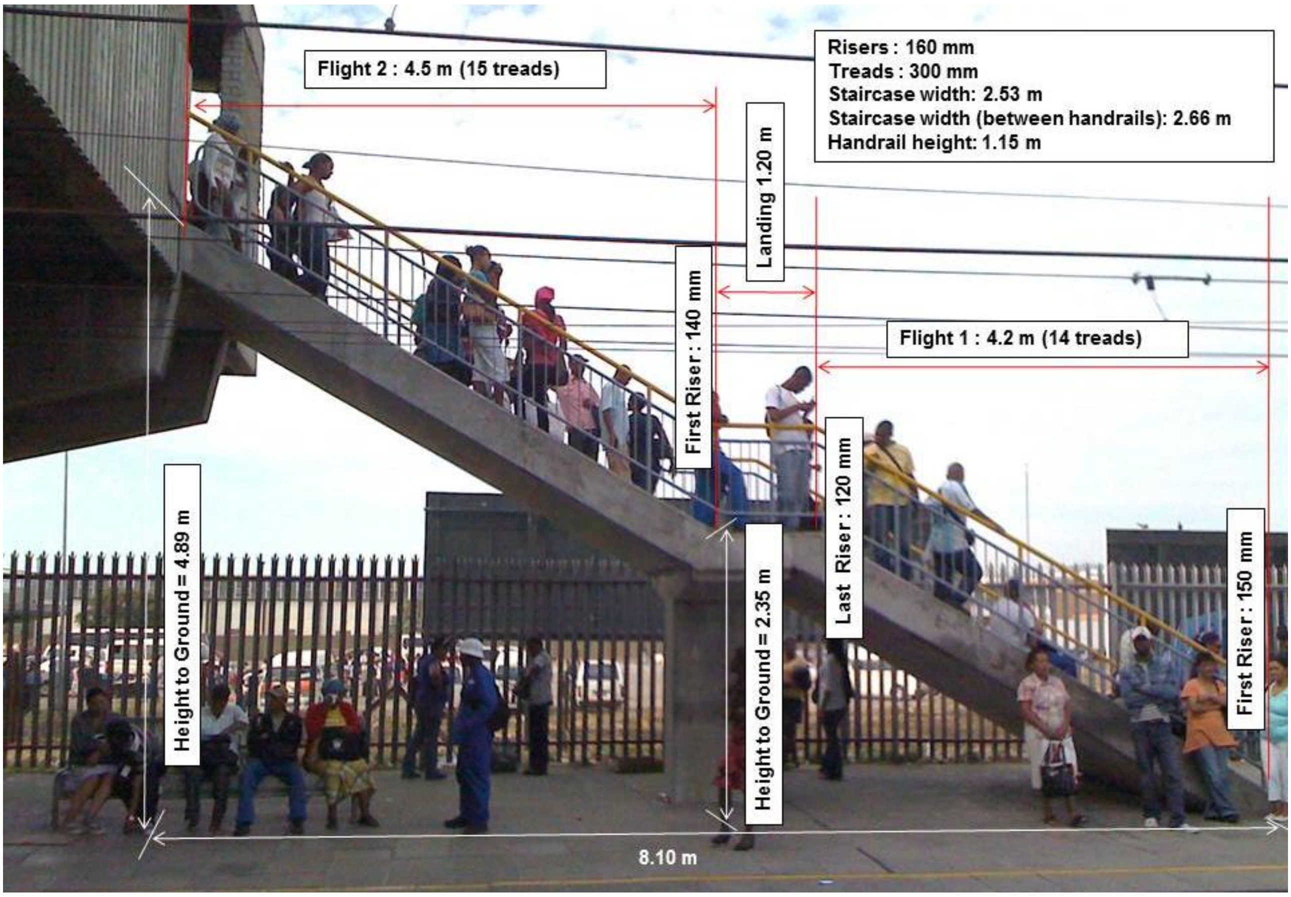
Area A : North Skywalk measurement area at Bonteheuwel station



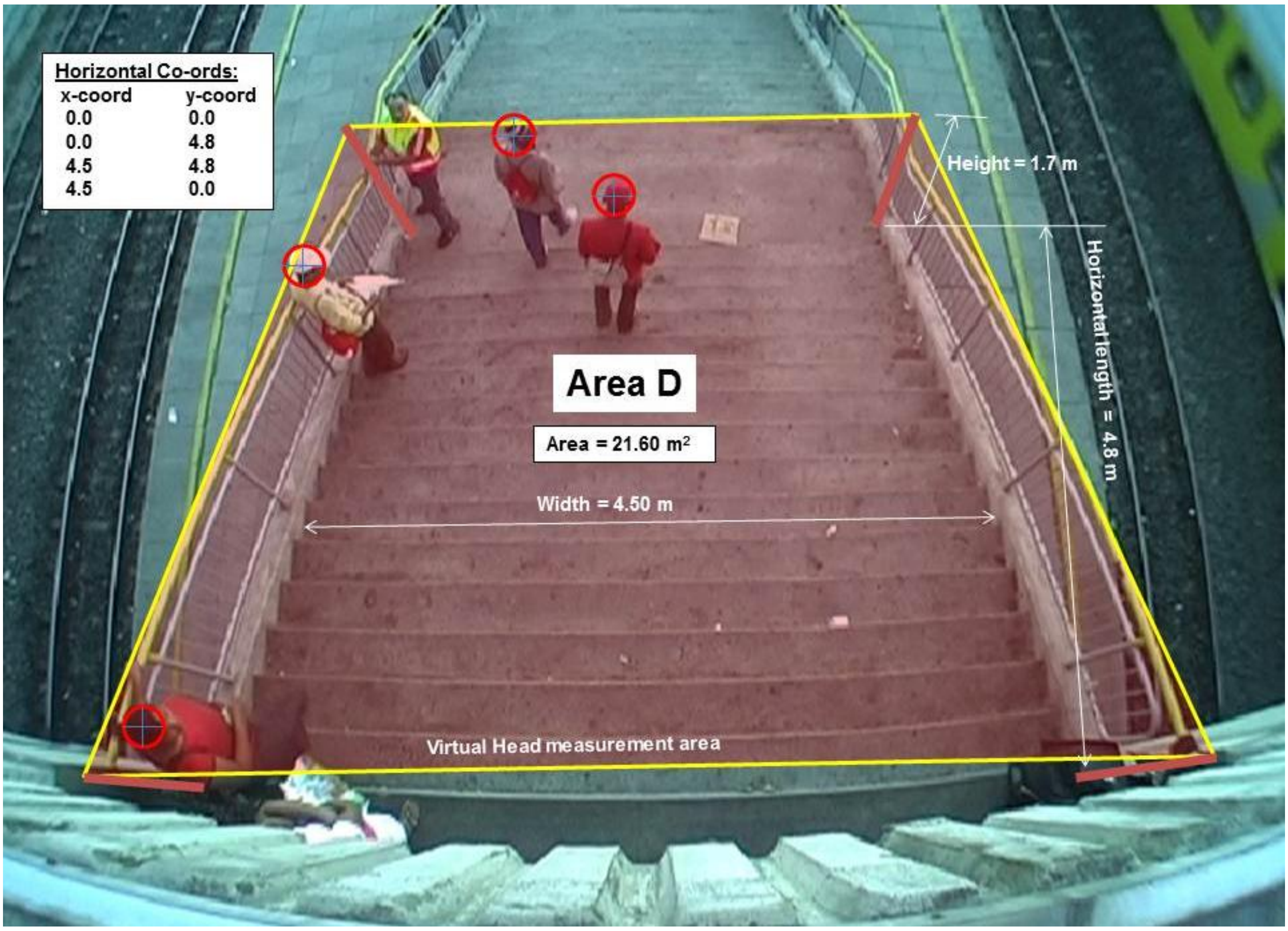
Area B : Platform measurement area at Bonteheuwel station (Platform 2)



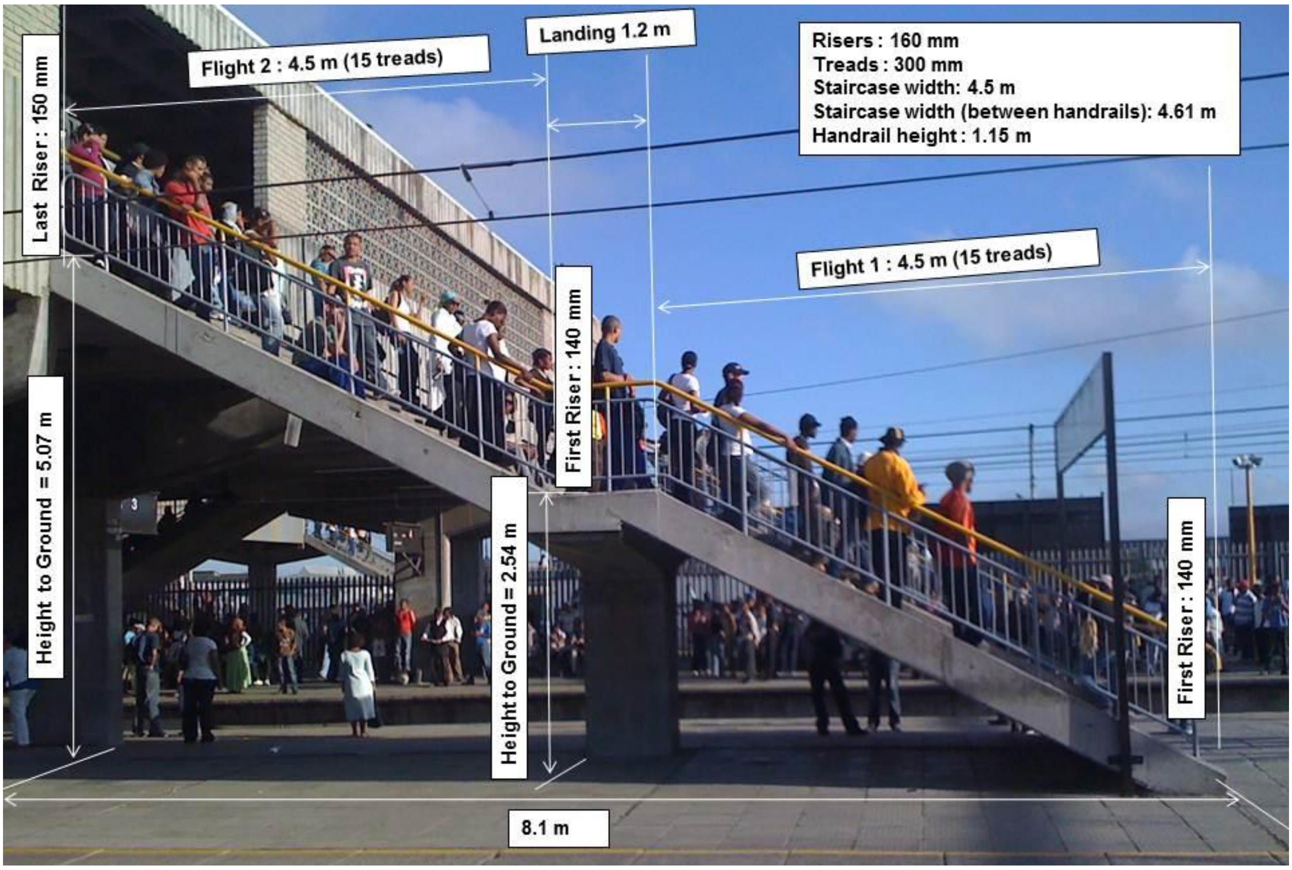
Area C : North (Narrow) Staircase measurement area at Bonteheuwel station



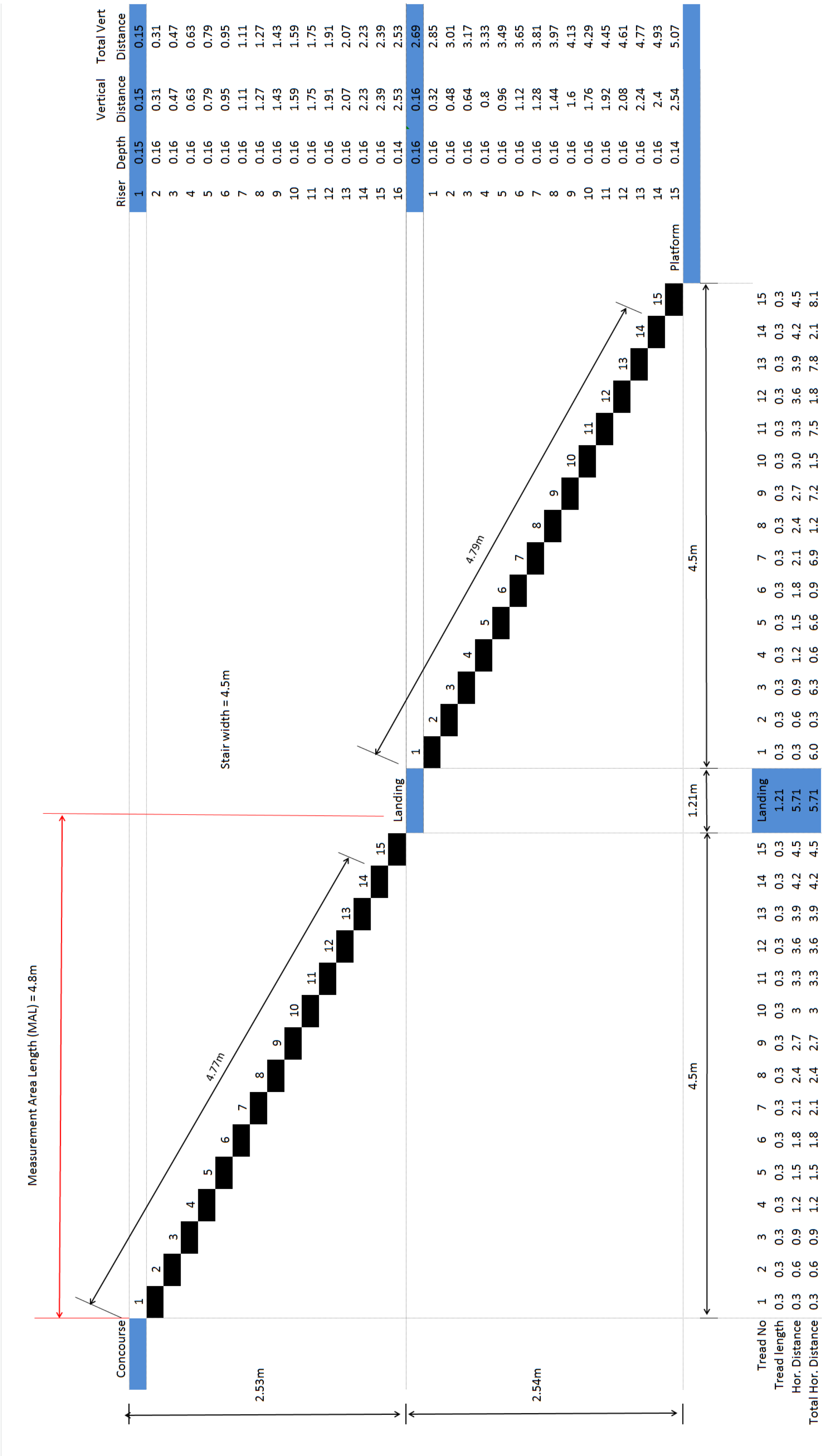
Area C : North (Narrow) Staircase dimensions at Bonteheuwel station



Area D : South (Wide) Staircase measurement area at Bonteheuwel station



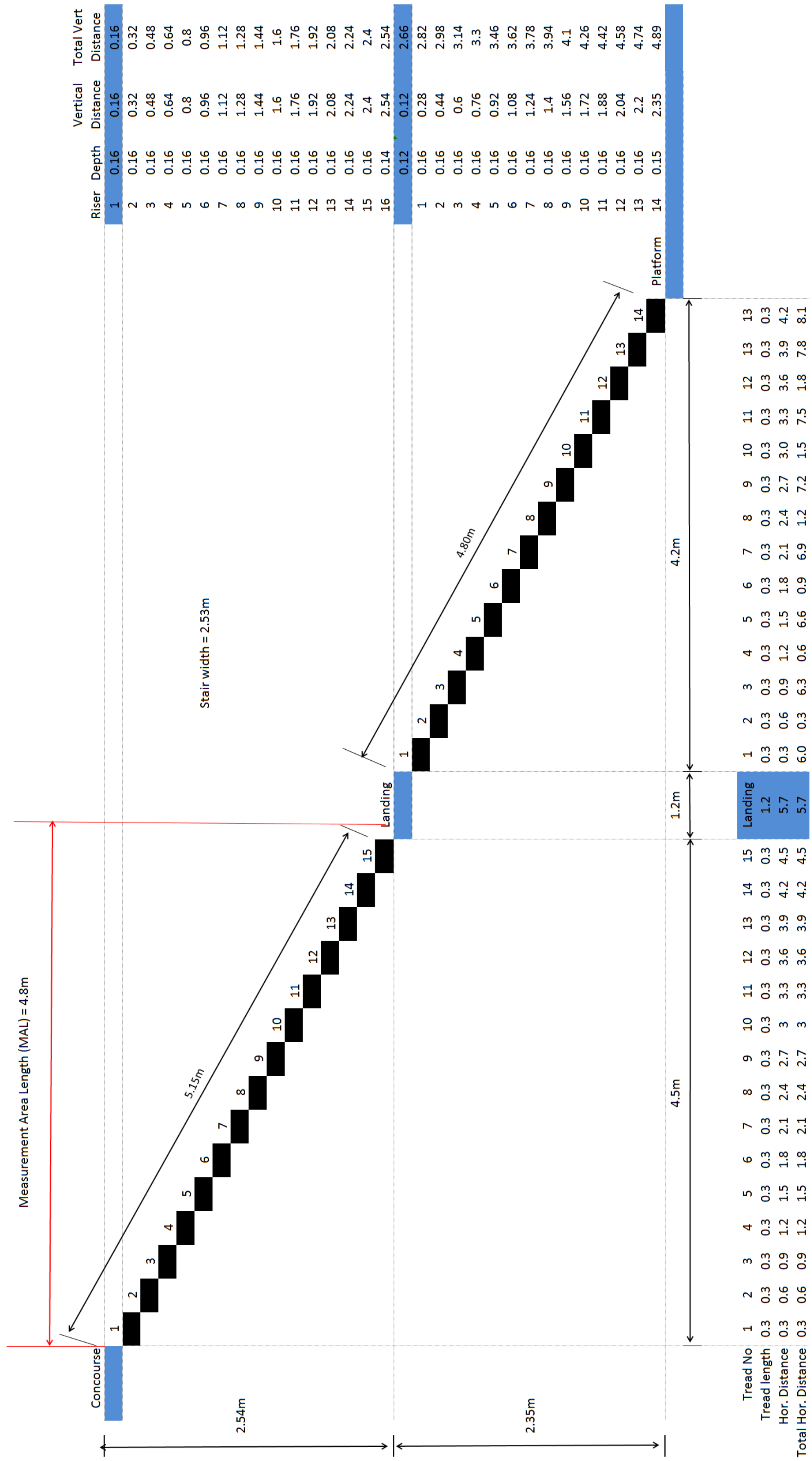
Area D : South (Wide) Staircase dimensions at Bonteheuwel station



Riser	Depth	Vertical Distance	Total Vert Distance
1	0.15	0.15	0.15
2	0.16	0.31	0.31
3	0.16	0.47	0.47
4	0.16	0.63	0.63
5	0.16	0.79	0.79
6	0.16	0.95	0.95
7	0.16	1.11	1.11
8	0.16	1.27	1.27
9	0.16	1.43	1.43
10	0.16	1.59	1.59
11	0.16	1.75	1.75
12	0.16	1.91	1.91
13	0.16	2.07	2.07
14	0.16	2.23	2.23
15	0.16	2.39	2.39
16	0.14	2.53	2.53
	0.16	0.16	2.69
1	0.16	0.32	2.85
2	0.16	0.48	3.01
3	0.16	0.64	3.17
4	0.16	0.8	3.33
5	0.16	0.96	3.49
6	0.16	1.12	3.65
7	0.16	1.28	3.81
8	0.16	1.44	3.97
9	0.16	1.6	4.13
10	0.16	1.76	4.29
11	0.16	1.92	4.45
12	0.16	2.08	4.61
13	0.16	2.24	4.77
14	0.16	2.4	4.93
15	0.14	2.54	5.07

Tread No	Tread length	Hor. Distance	Total Hor. Distance
1	0.3	0.3	0.3
2	0.3	0.6	0.6
3	0.3	0.9	0.9
4	0.3	1.2	1.2
5	0.3	1.5	1.5
6	0.3	1.8	1.8
7	0.3	2.1	2.1
8	0.3	2.4	2.4
9	0.3	2.7	2.7
10	0.3	3	3
11	0.3	3.3	3.3
12	0.3	3.6	3.6
13	0.3	3.9	3.9
14	0.3	4.2	4.2
15	0.3	4.5	4.5
Landing	1.21	5.71	5.71
1	0.3	0.3	6.0
2	0.3	0.6	0.3
3	0.3	0.9	6.3
4	0.3	1.2	0.6
5	0.3	1.5	6.6
6	0.3	1.8	0.9
7	0.3	2.1	6.9
8	0.3	2.4	1.2
9	0.3	2.7	7.2
10	0.3	3.0	1.5
11	0.3	3.3	7.5
12	0.3	3.6	1.8
13	0.3	3.9	7.8
14	0.3	4.2	2.1
15	0.3	4.5	8.1

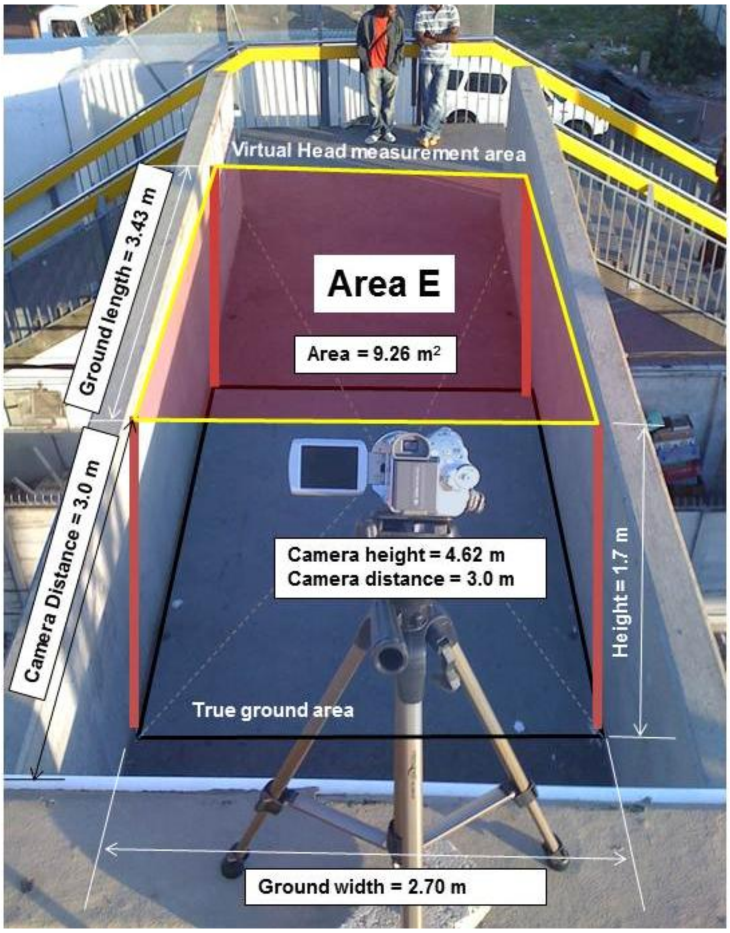
Area C : North (Narrow) Staircase long sectional dimensions at Bonteheuwel station



Riser	Depth	Vertical Distance	Total Vert Distance
1	0.16	0.16	0.16
2	0.16	0.32	0.32
3	0.16	0.48	0.48
4	0.16	0.64	0.64
5	0.16	0.8	0.8
6	0.16	0.96	0.96
7	0.16	1.12	1.12
8	0.16	1.28	1.28
9	0.16	1.44	1.44
10	0.16	1.6	1.6
11	0.16	1.76	1.76
12	0.16	1.92	1.92
13	0.16	2.08	2.08
14	0.16	2.24	2.24
15	0.16	2.4	2.4
16	0.14	2.54	2.54
	0.12	0.12	2.66
1	0.16	0.28	2.82
2	0.16	0.44	2.98
3	0.16	0.6	3.14
4	0.16	0.76	3.3
5	0.16	0.92	3.46
6	0.16	1.08	3.62
7	0.16	1.24	3.78
8	0.16	1.4	3.94
9	0.16	1.56	4.1
10	0.16	1.72	4.26
11	0.16	1.88	4.42
12	0.16	2.04	4.58
13	0.16	2.2	4.74
14	0.15	2.35	4.89

Tread No	Tread length	Hor. Distance	Total Hor. Distance
1	0.3	0.3	0.3
2	0.3	0.6	0.6
3	0.3	0.9	0.9
4	0.3	1.2	1.2
5	0.3	1.5	1.5
6	0.3	1.8	1.8
7	0.3	2.1	2.1
8	0.3	2.4	2.4
9	0.3	2.7	2.7
10	0.3	3	3
11	0.3	3.3	3.3
12	0.3	3.6	3.6
13	0.3	3.9	3.9
14	0.3	4.2	4.2
15	0.3	4.5	4.5
Landing	1.2	5.7	5.7
1	0.3	0.3	6.0
2	0.3	0.6	0.3
3	0.3	0.9	6.3
4	0.3	1.2	0.6
5	0.3	1.5	6.6
6	0.3	1.8	0.9
7	0.3	2.1	6.9
8	0.3	2.4	1.2
9	0.3	2.7	7.2
10	0.3	3.0	1.5
11	0.3	3.3	7.5
12	0.3	3.6	1.8
13	0.3	3.9	7.8
13	0.3	4.2	8.1

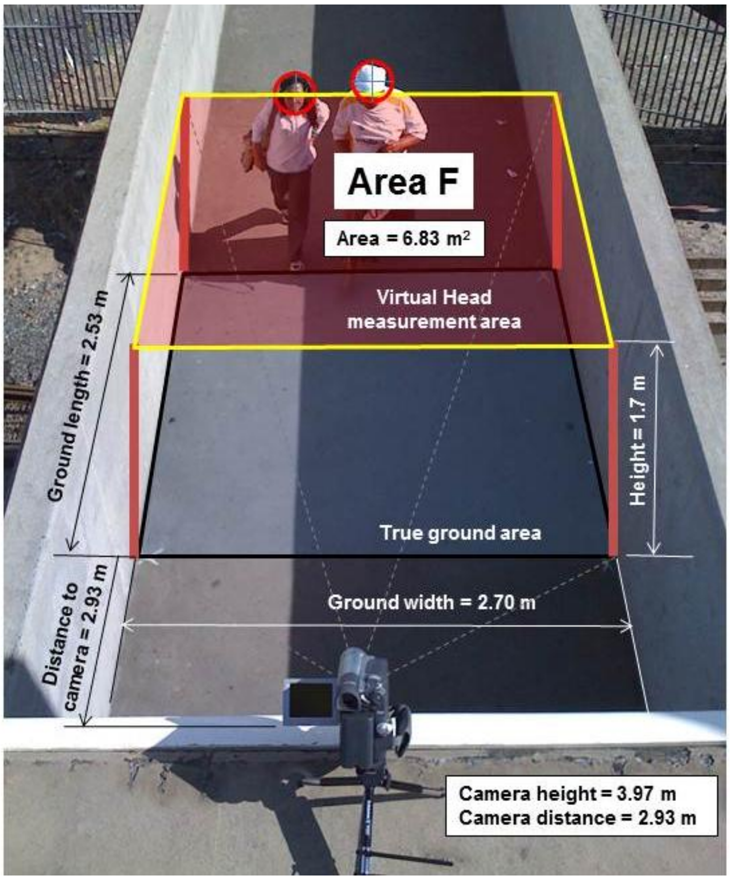
Area D : South (Wide) Staircase long sectional dimensions at Bonteheuwel station



Horizontal Co-ords:

x-coord	y-coord
0.0	0.0
0.0	3.43
2.70	3.43
2.70	0.0

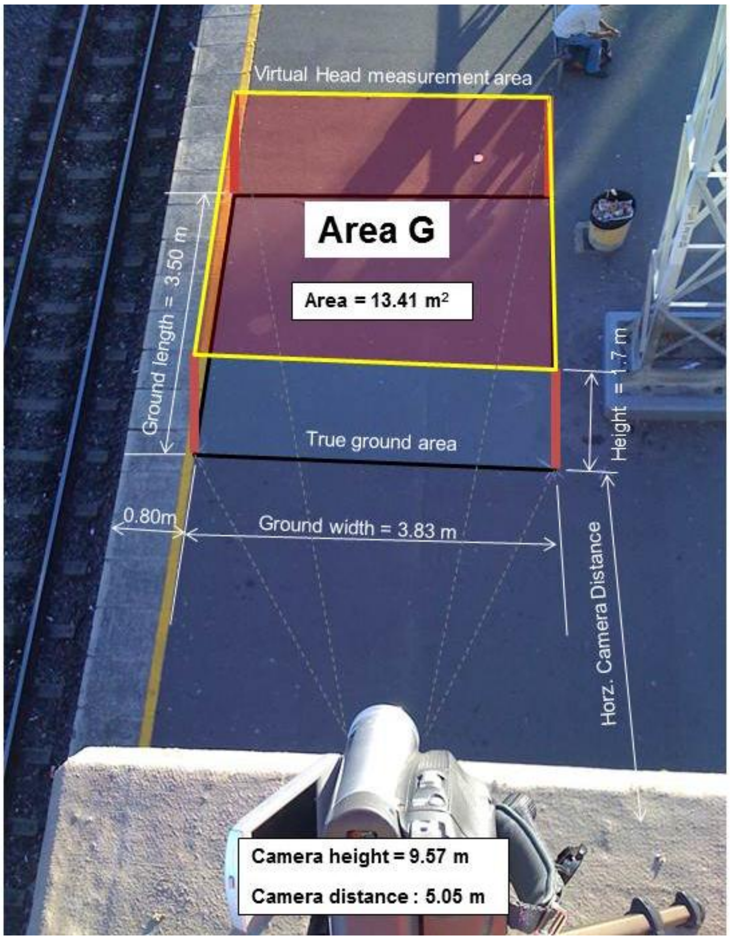
Area E : North Skywalk measurement area at Maitland station



Horizontal Co-ords:

x-coord	y-coord
0.0	0.0
0.0	2.53
2.70	2.53
2.70	0.0

Area F : South Skywalk measurement area at Maitland station



Horizontal Co-ords:	
x-coord	y-coord
0.0	0.0
0.0	3.50
3.83	3.50
3.83	0.0

Area G : Platform measurement area at Maitland station (Platform 6)

Photograph showing concourse camera placement above Measurement Area "A" at Bonteheuwel station

17. APPENDIX G: TRACKING PARAMETERS

The process of tracking using "*Headrecorder*" required that pedestrian attributes such as gender, age, person size, disabilities etc. be manually recorded separately for each pedestrian ID no. An output of the excel spreadsheet for recording such data and the classification of each column entry is described below and included as an example at the end of this appendix:

Tape:

This provides the record of the details of where and when the particular dataset was conducted.

ID No.:

Gives the ID number of the tracked or marked pedestrian.

Note that the pedestrian ID number is merely a sequential number from zero to the total number of pedestrians tracked. It is essential that every tracked pedestrian in the video recording is uniquely numbered in order to later associate the personal attributes (i.e. gender, body size etc.) determined separately by the data capturer. Because each frame number has an interval of 0.04 seconds, the frame number can be associated with a clock time, which together with the x and y co-ordinates, allows for the accurate trajectory tracking of each pedestrian.

Gender:

Classification was either "*m*" for male or "*f*" for female. Any uncertainty in gender classification was automatically allocated a "*marker*" classification and the microscopic particulars of that ID were ignored, although the "*markers*" contributed to the overall MA macroscopic density.

Age:

Initially, it was proposed that three age groups be identified viz. Child "*c*" less than 14 years of age; Adult, "*a*" between 14 and 65 years of age and Old, "*o*" for pedestrians over 65 years of age. It was however decided not to capture the age group attribute since it quickly became evident that most of the sample constituted adults in the 14 to 65 year category. Those that were not adults were identified as "*markers*" and ignored in the microscopic dataset.

Person Size:

For quantification of person size, a scoring system from 1 to 5 was used, defined as follows:

1: Lean/small built;

2: Slightly leaner than average but not thin;

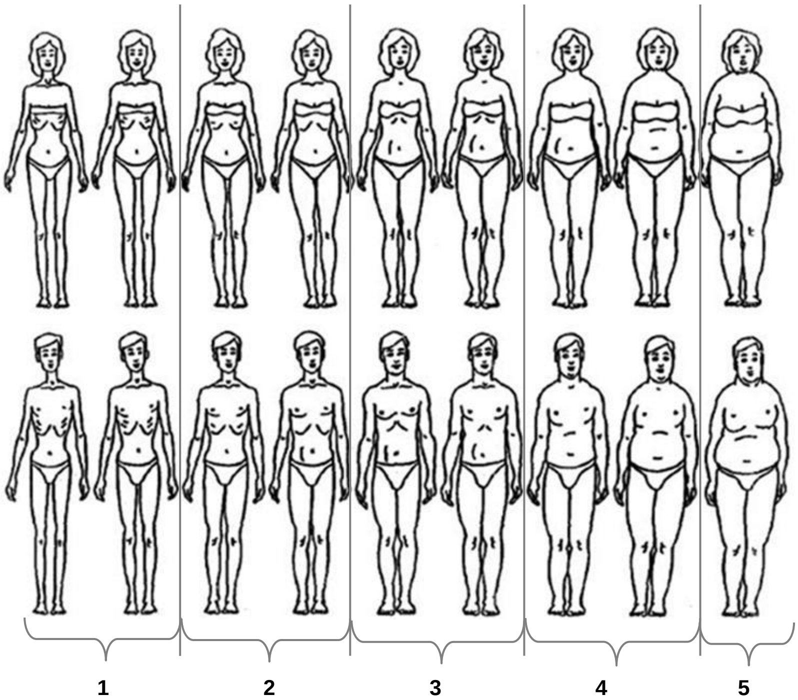
3: Average Build;

4: Slightly larger than average but not overweight;

5: Large/large built;

x: Marker.

To avoid different classifications for similar sized persons e.g. across recordings, a single resource was tasked with “*Person size*” tracking and identification to eliminate any potential personal bias in this subjective task. Figure G1 provides a representation of the person size classification used in the tracking process.



Legend :

1: Lean/small built

2: Slightly leaner than average but not thin

3: Average Build

4: Slightly larger than average but not overweight

5: Large/large built

x: Marker

Figure G1: Person Size Scaling used in the Tracking Process

Group size:

This attribute provides the number of persons walking in a group. For example, if pedestrian ID no’s 34 and 38 were walking together (identified by talking to each other or holding hands etc.) then both the ID no’s would have “*2*” in the “Group size” allocation.

Encumbrance:

This attribute indicated to what extent the pedestrian’s mobility was hindered through carrying of a piece of luggage and a scoring system of 0 (unencumbered) to 5 was used, defined as follows:

0: Nothing (unencumbered);

1: Bag/article carried in one hand;

2: Bag/article carried in both hands;

3: Rucksack/knapsack with both straps over the shoulders;

4: Slingbag with one strap over shoulder. This included rucksacks with one strap over the shoulder which also included large handbags;

5: Other items (affecting walking performance);

x: Marker.

Comment:

In the comment section, the enumerator was free to capture any relevant comment for the particular pedestrian ID, which included providing details on the type of luggage carried, unusual behaviours or type of mobility impairment observed etc.

Movement :

The movement attribute included either "*Wait*", "*Alight*", "*Board*" or "*Marker*" classifications, depending on the movement type observed and was captured for the platform dataset only. For the B&A data, the movement was captured as either "*Boarding*" or "*Alighting*".

All staircase recordings had an additional spreadsheet which provided the details of the train arrival and departure times. The frame no's when the trains arrived and departed were recorded including the line number and direction of travel as either "*in*" (citybound) or "*out*" (outbound). A sample of this spreadsheet is included below. Table G1 shows the details of the pedestrian attributes captured in addition to the tracking data.

Table G1: Details of Pedestrian Attributes Captured

Measurement Area	**Time**	**Gender**	**Person Size**	**Group Size**	**Encumbrance**	**Movement**
Platforms	✓	✓	✓	✓	✓	✓
Skywalks	✓	✓	X	X	X	X
Staircases	✓	✓	X	X	X	X
B&A	✓	X	X	X	X	✓

The dataset for the skywalks and staircases incorporated only the "*gender*" classification in addition to the "*Time*", "*Tape no*" and "*ID no*" attributes. This is because it was not possible to identify the other parameters due to the very high densities experienced on these measurement areas. The capturing of movement direction on the skywalks and staircases was not required as this was automatically calculated from the tracking co-ordinates and can be only one of two possible directions.

Tape	ID No.	Gender	Person Size	Group size	Mobility	Comment	Movement
6a	0	m	3	1	4		Wait
6a	1	m	3	1	4		Wait
6a	2	f	4	1	4		Wait
6a	3	f	4	1	4		Wait
6a	4	f	3	1	4		Wait
6a	5	f	3	1	4		Wait
6a	6	f	3	1	4		Wait
6a	7	f	4	1	4		Wait
6a	8	f	4	1	4		Wait
6a	9	f	2	1	4		Wait
6a	10	m	3	1	1		Wait
6a	11	m	3	1	4		Wait
6a	12	m	3	1	0		alight
6a	13	m	3	1	0		alight
6a	14	m	3	1	1		marker
6a	15	m	3	1	3		marker
6a	16	m	2	1	1		Wait
6a	17	m	3	1	1		alight
6a	18	m	2	2	0		alight
6a	19	m	3	1	1		alight
6a	20	m	4	1	4		alight
6a	21	m	3	1	4		alight
6a	22	m	3	1	3		alight
6a	23	m	3	1	4		alight
6a	24	m	5	1	1		alight
6a	25	f	4	1	4		alight
6a	26	m	3	2	0		alight
6a	27	m	3	1	0		alight
6a	28	m	3	1	4		alight
6a	29	m	3	1	4		alight
6a	30	f	3	1	1/4		alight
6a	31	m	4	1	0		alight
6a	32	m	3	1	4		alight
6a	33	m	5	1	4		alight
6a	34	m	2	1	1		alight
6a	35	m	3	1	0		alight
6a	36	m	2	1	0		alight
6a	37	m	3	1	4		alight
6a	38	m	3	1	4		alight
6a	39	m	3	1	4		alight
6a	40	f	3	1	4		alight
6a	41	f	5	1	4		alight
6a	42	m	3	1	4		alight
6a	43	m	4	1	4		alight
6a	44	m	3	1	3		alight
6a	45	m	3	1	4		alight
6a	46	f	4	1	4		alight
6a	47	f	3	1	4		alight
6a	48	m	3	2	4		alight
6a	49	m	3	2	0		alight
6a	50	m	3	1	4		alight
6a	51	m	3	1	4		alight
6a	52	m	3	1	0		alight
6a	53	m	3	1	1		alight
6a	54	m	3	1	1		alight
6a	55	m	3	2	0		alight
6a	56	m	4	2	0		alight
6a	57	m	3	1	0		alight
6a	58	m	3	1	4		alight
6a	59	m	3	1	4		alight
6a	60	m	4	1	4		alight

Train no	Frame arrive	Frame depart	line	direction
1	2716	3656	3	in
2	10266	11316	3	in
3	10276	11296	4	out
4	15546	16746	4	out
5	16026	16956	3	in
6	19176	20036	1	in
7	21666	22576	3	in
8	34206	35016	3	in
9	37326	38886	1	in
10	37756	38556	2	out
11	40516	41316	4	out
12	42546	43416	3	in
13	45296	46476	4	out
14	46036	46966	1	in

18. APPENDIX H: BOARDING AND ALIGHTING DATASHEET

Tape	hh	mm	ss	Direction	Line	Door Sample	Comment
42	0	13	22				train stops
42	0	13	27	a	3	1	
42	0	13	28	a	3	1	
42	0	13	29	a	3	1	
42	0	13	29	a	3	1	
42	0	13	30	a	3	1	
42	0	13	31	a	3	1	
42	0	13	31	a	3	1	
42	0	13	32	a	3	1	
42	0	13	32	a	3	1	
42	0	13	33	a	3	1	
42	0	13	34	a	3	1	
42	0	13	35	a	3	1	
42	0	13	36	a	3	1	
42	0	13	37	a	3	1	
42	0	13	59				train departs
42	0	30	35	a	3	1	
42	0	30	36	a	3	1	
42	0	30	36	a	3	1	
42	0	30	36				train stops
42	0	30	37	a	3	1	
42	0	30	37	a	3	1	
42	0	30	38	a	3	1	courtesy exit a
42	0	30	38	a	3	1	
42	0	30	38	a	3	1	
42	0	30	39	a	3	1	
42	0	30	39	a	3	1	
42	0	30	40	a	3	1	
42	0	30	40	a	3	1	
42	0	30	41	a	3	1	
42	0	30	41	a	3	1	
42	0	30	42	a	3	1	
42	0	30	42	a	3	1	
42	0	30	43	a	3	1	
42	0	30	43	a	3	1	
42	0	30	43	a	3	1	
42	0	30	44	a	3	1	
42	0	30	45	a	3	1	
42	0	30	45	a	3	1	
42	0	30	46	a	3	1	
42	0	30	46	a	3	1	
42	0	30	46	a	3	1	
42	0	30	47	a	3	1	
42	0	30	47	a	3	1	
42	0	30	47	a	3	1	
42	0	30	48	a	3	1	
42	0	30	49	a	3	1	
42	0	30	49	a	3	1	
42	0	30	49	a	3	1	
42	0	30	49	a	3	1	
42	0	30	50	a	3	1	
42	0	30	50	a	3	1	
42	0	30	51	a	3	1	
42	0	30	51	a	3	1	
42	0	30	52	a	3	1	
42	0	30	52	a	3	1	
42	0	30	52	a	3	1	
42	0	30	52	a	3	1	

19. APPENDIX I: *HEADRECORDER*/*HEAD PLAYBACK* USER INSTRUCTIONS

***HEADRECORDER* / *HEADPLAYBACK* USER INSTRUCTIONS**

INTRODUCTION

There are two '.exe' files (Headrecorder.exe and Headplayback.exe) in the program suite described as follows:

'HeadRecorder.exe' loads the video and allows the user to setup a rectangle to define the measurement area[g]. The user can then insert (click) target markers on all targets (pedestrians) in each frame and then save that information to a '.txt' file (The target markers contains the screen x,y image coordinates of the target in that frame).

If an enumerator incorrectly left-clicks the location of a person's head in a certain frame, then it is possible to undo the incorrect point and data point information (with a right-click) and re-click the correct position and the rewrite the correct co-ordinates to the text file (with a left-click).

'HeadPlayback.exe' loads the '.txt' file generated by the previous '.exe' file and converts the image-coordinates of each target to real-world coordinates and displays their position in the given measurement area. Note that the measurement area does not have to be a perfect rectangle in real-world coordinates and can be any convex 4-point polygon. It also displays some calculated information such as the average density and average speed of the targets for each frame (averages are calculated over a sample window). The user can then save this calculated information and save it to a '.csv' file. The '.csv' file can then be opened in MS Excel for further processing.

SETTING FILES

Each '.exe' has a corresponding settings file viz. 'Recorder_Settings.txt' and 'Playback_Settings.txt' associated with 'HeadRecorder.exe' and 'HeadPlayback.exe' respectively. These files contain all the information that each '.exe' file requires to run without the use of arguments (thus eliminating the need for console loading). The settings can be changed by opening a file in notepad and editing the default values of each setting.

'Recorder_Settings.txt' contains the following default settings:

Video_dir
- Default: test.avi
- Description: directory path to the video file.

[g] *The measurement area (usually a rectangle) is constructed counter clockwise (starting from the back left co-ordinate as viewed by observer). In real-world coordinates [x,y] the sequence is, for example [0,0], [0,20], [10,20], [10,0]. Note that for screen coordinates, the origin is at the top left-hand corner. Positive x-axis is towards the right and positive y-axis is downwards.*

Save_dir

- Default: test_save.txt
- Description: directory path to the save file (.txt) that will store the data structure information.

VFlip

- Default: 1
- Description: set vertical flip ON(1) or OFF(0).

Highlights

- Default: 1
- Description: set highlights ON(1) or OFF(0).

Crosshair_scale

- Default: 1.0
- Description: Sets the scale of the crosshair, 1 = Normal size.

'Playback_Settings.txt' contains the following settings:

Data_dir

- Default: test_save.txt
- Description: directory path to the save file (.txt) generated by 'HeadRecorder.exe'

Save_dir

- Default: playback_save.csv
- Description: directory path to the save file (.csv) that will contain the calculated information.

Sample_window

- Default: 10
- Description: the number of frames over which the averages are calculated.

Real_Points

- Default: 0.0 0.0
0.0 20.0
10.0 20.0
10.0 0.0
- Description: the four real-world coordinates that define the area of interest.

HEADRECORDER

Double click on the 'HeadRecorder.exe' to start the program. As it starts, it will load the settings from 'Recorder_Settings.txt' and display the help message. Read the help message to see what keys are used and what their functions are. In the display window, the first frame of the video will be shown.

The program is now in *Setup Mode*. Here the user can setup the (measurement area) rectangle by left-clicking the corners in sequence described above. Right-clicking will remove the last corner for relocation. Once the desired rectangle is complete, press '*d*' for '(d)one'.

Note that if a valid save file is loaded once the program is executed, the measurement area rectangle will already be defined, but can be edited by redefining the corners with a right-click mouse action, otherwise press '*d*' to continue.

The program is now in *Target Mode*. The mouse icon will change into a target crosshair and display the current target number. The user can now left-click to mark a target with the current target number. Press '*n*' and '*b*' to increase and decrease the target number respectively. Each frame contains a list of targets in that frame, if a target is marked that already exists within the target list, the target is simply replaced.

Navigate through the video by using '>' and '<' to go forward and backward respectively, marking the target positions in each frame. If the end of the file is reached, the target list of each frame will be saved to a '.txt' file (Save_dir). Otherwise press '*s*' to save manually. If a valid save file has been loaded, the targets might be marked already, but the user is free to redefine their coordinate locations and save the edited information.

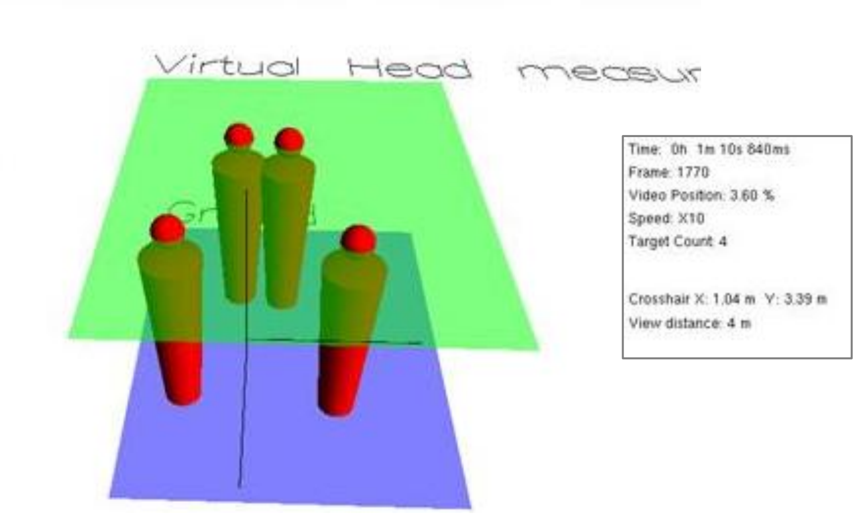
To measure the head position of every pedestrian in every frame, the "*Headrecorder"* software was provided with a target crosshair tool to target each pedestrians' head and extract the screen x and y coordinates upon a mouse click. The coordinates were automatically exported and saved to a text file which could be selected for every frame if so required. The head of each pedestrian was targeted as the representative body part since, if other parts of the body were going to be used, it would be difficult to be consistent for all pedestrians and tracking body parts lower than the head (e.g. like feet) would be impossible at high densities. The limitation of this type of tracking process is that the height of each pedestrian is assumed to be identical to the "*reference plane*" at the benchmark height of 1.65 m above the ground.

HEADPLAYBACK

Double-click on the 'HeadPlayback.exe' to execute the program. As the program intiates, it will load the settings from 'Playback_Settings.txt' and display the help message. Read the help message to see what keys are used and what their functions are.

The information contained in the save file generated by 'HeadRecorder.exe' is loaded and displayed frame by frame. Navigate through the sequence by using '>' and '<' to go forward and backward respectively. Press '*n*' and '*b*' to increase and decrease the size of the sample window respectively. Press '*s*' to save the calculated information to a '.csv' file. This File can be edited in MS Excel.

The 3D representative playback function of the pedestrians already tracked to visually verify that the capture process had been done without data gaps. This proved useful at low densities but is not practical at high densities. The figure below shows the typical "*Headplayback*" screen.



Acknowledgements:
User Instruction manual Author: François Singels, edited by L. Hermant
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Cell phone: 084 811 5889

20. APPENDIX J: TEXT FILE OUTPUT OF *HEADRECORDER* SOFTWARE

Total_frames 49200

Points 176 106 57 423 616 402 524 91

Frame 5430 217240 target_count 18 ID 312 x 404 y 45

Frame 5431 0 target_count 0

Frame 5432 0 target_count 0

Frame 5433 0 target_count 0

Frame 5434 0 target_count 0

Frame 5435 0 target_count 0

Frame 5436 0 target_count 0

Frame 5437 0 target_count 0

Frame 5438 0 target_count 0

Frame 5439 0 target_count 0

Frame 5440 217640 target_count 17 ID 312 x 409 y 33 ID 313 x 378 y 47

Frame 5441 0 target_count 0

Frame 5442 0 target_count 0

Frame 5443 0 target_count 0

Frame 5444 0 target_count 0

Frame 5445 0 target_count 0

Frame 5446 0 target_count 0

Frame 5447 0 target_count 0

Frame 5448 0 target_count 0

Frame 5449 0 target_count 0

Frame 5450 218040 target_count 15 ID 312 x 419 y 20 ID 313 x 379 y 36

Frame 5451 0 target_count 0

Frame 5452 0 target_count 0

Frame 5453 0 target_count 0

Frame 5454 0 target_count 0

Frame 5455 0 target_count 0

Frame 5456 0 target_count 0

Frame 5457 0 target_count 0

Frame 5458 0 target_count 0

Frame 5459 0 target_count 0

Frame 5460 218440 target_count 15 ID 313 x 386 y 26

Frame 5461 0 target_count 0

Frame 5462 0 target_count 0

Frame 5463 0 target_count 0

Frame 5464 0 target_count 0

Frame 5465 0 target_count 0

Frame 5466 0 target_count 0

Frame 5467 0 target_count 0

Frame 5468 0 target_count 0

Frame 5469 0 target_count 0

Frame 5470 218840 target_count 14 ID 313 x 381 y 17

Frame 5471 0 target_count 0

Frame 5472 0 target_count 0

Frame 5473 0 target_count 0

Frame 5474 0 target_count 0

Frame 5475 0 target_count 0

Frame 5476 0 target_count 0

Frame 5477 0 target_count 0

Frame 5478 0 target_count 0

21. APPENDIX K: STATISTICAL THEORY

INTRODUCTION

This appendix discusses the regression analysis procedure and the coefficients that describe the regression model and significance of the correlation for simple linear regression of two variables as well as the ARIMA time-series model. This appendix references *Applied Statistics and Probability for Engineers* (Montgomery and Runger 2007) and the reader is referred to this source for the complete mathematical derivation of the presented equations.

SIMPLE LINEAR REGRESSION

Simple linear regression is linear regression between only two variables, the dependant variable (*y*) that is adjusted according to a single independent variable (*x*). The relationship between the variables is assumed to be linear if the points of the data appear to be scattered randomly about a straight line. The method for calculating a regression line, the level of variation in the data and the measure of significance of the regression analysis and the fit to the actual data are considered in the following paragraphs.

The Linear Regression Equation

Data that is grouped around a straight line can be described by Equation K-1 where ϵ is the random error that describes the vertical offset of an actual data point from the regression curve with Equation K-2, and an intercept, β_0 and gradient of β_1.

$$y = \beta_0 + \beta_1 . x + \in \quad \text{Equation K-1}$$

$$y = \beta_0 + \beta_1 . x \quad \text{Equation K-2}$$

The regression coefficients, β_0 and β_1, are determined using the "*least squares*" method, which identifies the linear equation that produces the smallest sum of errors (ϵ) over the entire data set. These coefficients are calculated by differentiating the summed squared errors (ϵ^2) with respect to β_0 and β_1, and equating these differentials to zero. This method, which is presented in detail by Montgomery and Runger (2007), results in the following equations that estimate the regression coefficients:

$$\beta_0 = \bar{y} - \beta_1 . \bar{x} \quad \text{Equation K-3}$$

$$\beta_1 = \frac{S_{xy}}{S_{xx}} \quad \text{Equation K-4}$$

where $\bar{x}$ and $\bar{y}$ are the average values of the independent and dependent variables respectively, calculated with Equation K-5, and S_{xy} and S_{xx} are calculated with Equation K-6 and Equation K-7 respectively:

$$\bar{x} = \sum_{i=1}^{n} x_i / n \quad \text{Equation K-5}$$

$$S_{xy} = \sum_{i=1}^{n} x_i \, y_i - \frac{(\sum x_i)(\sum y_i)}{n} \quad \text{Equation K-6}$$

$$S_{xx} = \sum_{i=1}^{n} x_i^2 - \frac{(\sum x_i)^2}{n} \quad \text{Equation K-7}$$

Data Variance

The variance, σ^2, of the error, ϵ, in Equation K-1, is a measure of the dispersion of the actual data around the regression curve. Variance is calculated with Equations K-8, K-9 and K-10:

$$\sigma^2 = \frac{SS_E}{n-2} \qquad \text{Equation K-8}$$

$$SS_E = SS_T - \beta_1 S_{xy} \qquad \text{Equation K-9}$$

$$SS_T = \sum_{i=1}^{n}(y_i - \bar{y})^2 = \sum_{i=1}^{n} {y_i}^2 - n\bar{y}^2 \qquad \text{Equation K-10}$$

Coefficient of Determination

The Coefficient of Determination, denoted R^2, is a measure of how well the regression model fits the actual data, that is, it describes the adequacy of the model. R^2 indicates the proportion of total variability in the dataset that is accounted for by the regression model. R^2 is calculated by Equation K-11, presented below:

$$\boldsymbol{R^2 = 1 - \frac{SS_E}{SS_T}} \qquad \text{Equation K-11}$$

The value of the R^2 coefficient can range between 0.0 and 1.0 ($0 \leq R^2 \leq 1$), where a value approaching 1.0 indicates a good correlation between the data and regression model. An R^2 value of 1.0 indicates that 100% of the variability of the data is accounted for by the regression equation, meaning that all the data points lie exactly along the regression line and the error terms ϵ, are all equal to zero. The more dispersed the data points are around the regression line, the lower the R^2 value will be. A low R^2 value therefore indicates that the model does not accurately describe the variance of a large proportion of the dataset, indicating that the regression model may not be adequate to describe the dataset.

The coefficient of determination should however not be exclusively used to determine the suitability of a regression model. Data which is widely dispersed around a regression line and therefore has a relatively low R^2 value, may still have a statistically significant relationship between the independent and dependant variables. The statistical significance of a regression model is described below.

STATISTICAL SIGNIFICANCE OF REGRESSION USING THE *P*- AND *T*-STATISTIC

A regression model must be evaluated to assess its ability to adequately describe a dataset. This is achieved using Hypothesis Tests which investigate statistical hypotheses regarding the model parameters (that is the slope and intercept values of the linear regression equation) with *t*-Tests. The method detailed below tests the relevance of the slope of the regression line, but is also applicable to test the intercept. Two hypotheses are made, namely the null hypothesis which states that the slope of the regression equation is equal to a constant (H_0: $\beta_1 = c$), and the alternative hypothesis that the slope does not equal the constant c (H_1: $\beta_1 \neq c$). The null hypothesis is rejected if the absolute value of the *t*-Statistic, calculated with Equation K-12, is greater than the value of the *t*-distribution with n-2 degrees of freedom (where n is the number of observations) and a confidence of 100(1-α)% that the slope is described by β_1, represented by Equation K-13.

$$T_0 = \frac{\beta_1 - c}{\sqrt{\sigma^2 / S_{xx}}}$$ Equation K-121

$$|\boldsymbol{T_0}| > \boldsymbol{t_{\alpha/2,n-2}}$$ Equation K-13

For 95% confidence in the value of the slope and more than 120 observations, the *t*-distribution has a value of $t_{\alpha/2,n-2} = t_{0.025,\infty} = 1.960$. In order for the null hypothesis to be rejected, the *t*-Statistic must have an absolute value of greater than 1.960.

When testing the significance of the linear relationship between the dependant *y* variable and independent *x* variable, a null hypothesis is selected which states that the slope β_1 of the regression equation is equal to zero, (H_0: $\beta_1 = 0$). The constant *c* in Equation K-12 is therefore substituted with zero. A slope of 0% would indicate that no correlation exists between *y* and *x*. Therefore, if a statistically significant correlation exists and the regression model is satisfactory, the null hypothesis must be rejected by proving that the *t*-Statistic is greater that the value of the *t*-distribution, i.e. Equation K-13 holds true.

THE ARIMA TIME-SERIES MODEL

The acronym ARIMA stands for "*Auto-Regressive Integrated Moving Average*" and is used to statistically test the differences between the time-series output of the SP-model versus the corresponding time-series results of the VISSIM microscopic model. Lags of the differenced series appearing in the forecasting equation are called "*auto-regressive*" (AR) terms, lags of the forecast errors are called "*moving average*" (MA) terms, and a time series which needs to be differenced to be made stationary is said to be an "*integrated*" version of a stationary series.

A nonseasonal ARIMA model is classified as an "ARIMA(*p*,*d*,*q*)" model, where:

p is the number of autoregressive terms,
d is the number of nonseasonal differences, and
q is the number of lagged forecast errors in the prediction equation.

To identify the appropriate ARIMA model for a time series comparison, we begin by identifying the order(s) of differencing needing to stationarize the series and remove the gross features of seasonality, perhaps in conjunction with a variance-stabilizing transformation such as logging or deflating. The three types of ARIMA models used in this study are:

ARIMA(1,1,0) or AR(1): A differenced first-order autoregressive model represented by the following prediction equation:

$$\hat{Y}(t) = \mu + \emptyset_1 . Y(t-1)$$

This is a first-order autoregressive, or AR(*1*) model with one order of nonseasonal differencing and a constant term denoted by *μ* and the autoregressive coefficients is denoted by *Φ*, in keeping with the terminology for ARIMA models.

A more generic multiple lag AR(*n*) model can be represented by:

$$\hat{Y}(t) = \mu + \emptyset_1 . Y(t-1) + \emptyset_2 . Y(t-2) + \cdots + \emptyset_n . Y(t-n))$$

ARIMA(0,1,1) or MA(1): Another strategy for correcting autocorrelated errors is the simple exponential smoothing model. By taking the most recent observation as the forecast of the next observation, it is better to use an average of the last few observations in order to filter out the noise and more accurately estimate the local mean. The simple exponential smoothing model uses an exponentially weighted moving average of past values to achieve this effect. The prediction equation for the simple exponential smoothing model can be written as:

$$\hat{Y}(t) = \theta_1 . e(t-1)$$

where *e(t-1)* denotes the error at period *t* - 1. The coefficient of the lagged forecast error is denoted by θ. When a lagged forecast error is included in the prediction equation as shown above, it is referred to as a "*moving average*" (MA) term. The simple exponential smoothing model is therefore a first-order moving average MA(1) model with one order of nonseasonal differencing and no constant term. The generic MA(*n*) model is represented by:

$$\hat{Y}(t) = \theta_1 . e(t-1) + \theta_2 . e(t-2) + \cdots + \theta_n . e(t-n)$$

A mixed ARIMA(1,1,1) model: The features of autoregressive and moving average models can be "*mixed*" in the same model. For example, an ARIMA(1,1,1) model with a constant would have the prediction equation:

$$\hat{Y}(t) = \mu + \emptyset_1 . Y(t-1) + \emptyset_2 . Y(t-2) + \theta_1 . e(t-1) + \theta_2 . e(t-2)$$

APPLICATION OF THE ARIMA MODEL

The determination of the most appropriate ARIMA model viz, AR(*n*), MA(*n*) or ARIMA(1,1,1) to apply to the difference of the time-series data results is by testing the significance of the lag correlation terms. The *P*-statistic of the highest order (or first) lag correlation term that is within the 5% confidence level defines the lag differencing requirement for the particular model. The significance of each of the lag correlation terms is first tested for the AR model, failing which the same process is repeated for the MA model. If no lag correlation terms are statistically significant for either the AR or MA model, the ARIMA model is finally tested for significance. Should no lag correlation terms be significant, it indicates that there are insufficient data points to determine the appropriate model.

Once the appropriate ARIMA model is selected, then the constant term μ is tested to determine if it is significantly different from zero (Null hypothesis H_o: $\mu = 0$). Significance is determined by calculating the *P*-statistic for μ and the result would then indicate if the model results were different from each other.

If the *P*-statistic of the constant term μ is greater than the 5% level of significance (i.e. *P*-statistic > 0.05), it indicates that the null hypothesis (H_o) is true (i.e. no significant difference) and therefore it can be concluded that there is a correlation between the two time-series models being tested.

22. APPENDIX L: SP-MODEL USER MANUAL

23. APPENDIX M: SP-MODEL OUTPUTS: CENTURY CITY STATION (SCENARIO 1)

TRAIN COACH DETAILS

Train Code	Train Type	Class	No. Doors per coach side	Overall coach Length (m)	Door width (m)	Seating Capacity (pax)	Stand Capacity (pax)	Total Capacity' (pax)
5M2A-1	Motor	Metro+	1	19.45	1.47	55	20	75
5M2A-2	Motor	Metro	1	19.45	1.47	44	71	115
5M2A-3	Trailer	Metro+	2	18.26	1.47	70	35	105
5M2A-4	Trailer	Metro+	3	18.26	1.47	70	35	105
5M2A-5	Trailer	Metro	3	18.26	1.47	60	100	160
8M-1	Motor	Metro	4	22.94	1.5	56	190	246
8M-2	Trailer	Metro	4	22.94	1.5	64	198	262
10M5	Trailer	Metro	3	18.26	1.47	48	80	128
10M3-1	Motor	Metro	1	19.45	1.47	24	100	124
10M3-2	Trailer	Metro	2	18.26	1.47	64	100	164
10M3-3	Trailer	Metro	2	18.26	1.47	64	100	164
Spare								

TRAIN TYPE

Train Type 1 | **Train Type 2**

No.	Coach	Type	Length	Doors	Capacity	Coach	Type	Length	Doors	Capacity
1	8M-1	Motor	22.94	4	246	Empty	0	0	0	0
2	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
3	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
4	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
5	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
6	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
7	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
8	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
9	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
10	8M-2	Trailer	22.94	4	262	Empty	0	0	0	0
11	Empty	0	0	0	0	Empty	0	0	0	0
12	Empty	0	0	0	0	Empty	0	0	0	0
13	Empty	0	0	0	0	Empty	0	0	0	0
14	Empty	0	0	0	0	Empty	0	0	0	0

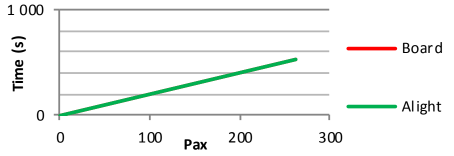
Comments:

1. None
2. None

DEFAULT PARAMETERS (PAGE 1)

B&A Details:

Boarding: Boarding time (sec) = α. boarding pax + β :	α =	2	β =	0
Alighting: Alighting time (sec) = α. alighting pax + β :	α =	2	β =	0

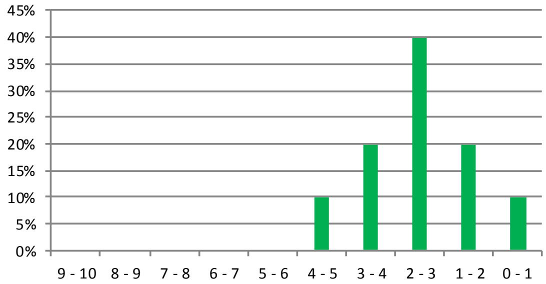


Note that the formula refers to the total alighting or boarding time and applies to a single coach door.

Passenger Arrival Rate (PAR):
*Time is t prior to train departure

Time* (min)	Pax (%)	Time* (min)	Pax (%)
9 - 10	0.0%	4 - 5	10.0%
8 - 9	0.0%	3 - 4	20.0%
7 - 8	0.0%	2 - 3	40.0%
6 - 7	0.0%	1 - 2	20.0%
5 - 6	0.0%	0 - 1	10.0%

Total: 100% ok

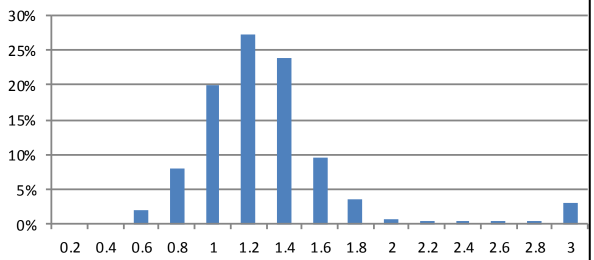


Walking Histogram

Platforms: Alighting

Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)
0.2	0.0%	1.2	27.3%	2.2	0.5%
0.4	0.0%	1.4	23.7%	2.4	0.5%
0.6	2.0%	1.6	9.5%	2.6	0.6%
0.8	7.9%	1.8	3.6%	2.8	0.4%
1	20.0%	2	0.8%	3	3.2%

Total: 100.0% ok

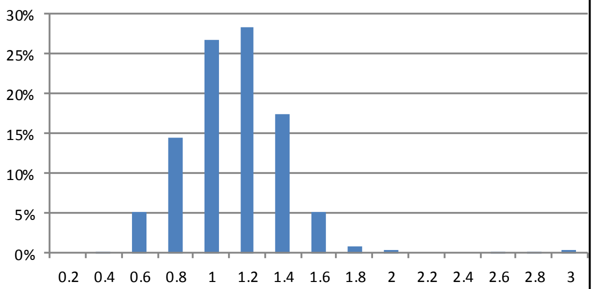


Walking Histogram

Platforms: Boarding

Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)
0.2	0.0%	1.2	28.4%	2.2	0.0%
0.4	0.1%	1.4	17.5%	2.4	0.0%
0.6	5.3%	1.6	5.3%	2.6	0.1%
0.8	14.5%	1.8	0.9%	2.8	0.1%
1	26.9%	2	0.4%	3	0.5%

Total: 100.0% ok

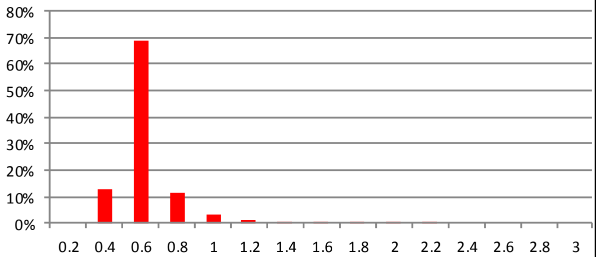


Walking Histogram

Stairs: Up Direction

Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)
0.2	0.0%	1.2	1.2%	2.2	0.1%
0.4	13.2%	1.4	0.5%	2.4	0.0%
0.6	68.6%	1.6	0.8%	2.6	0.0%
0.8	11.7%	1.8	0.6%	2.8	0.0%
1	3.1%	2	0.2%	3	0.0%

Total: 100.0% ok

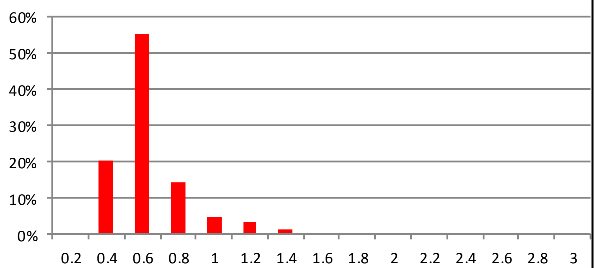


Walking Histogram

Stairs: Down Direction

Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)
0.2	0.0%	1.2	3.2%	2.2	0.0%
0.4	20.5%	1.4	1.4%	2.4	0.0%
0.6	55.3%	1.6	0.5%	2.6	0.0%
0.8	14.2%	1.8	0.2%	2.8	0.0%
1	4.6%	2	0.1%	3	0.0%

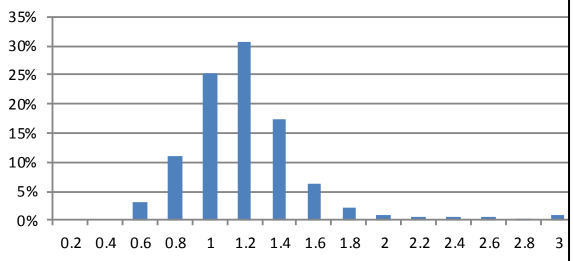
Total: 100.0% ok



DEFAULT PARAMETERS (PAGE 2)

Walking Histograms (continued):

	Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)	Speed (m/s)	Pax (%)
Skywalk	0.2	0.0%	1.2	30.5%	2.2	0.6%
	0.4	0.0%	1.4	17.5%	2.4	0.5%
	0.6	3.2%	1.6	6.4%	2.6	0.5%
Total:	0.8	11.1%	1.8	2.3%	2.8	0.4%
100.0% ok	1	25.1%	2	1.0%	3	0.9%



Level of Service Criteria

Flow Rate (q) LOS: Upper LOS level	Flow Rate q (p/m/min): Skywalk	Stairs
A	23	16
B	33	23
C	49	33
D	66	43
E	82	56
F	>82	>56

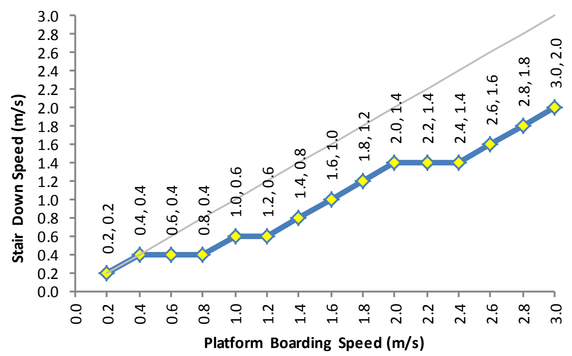
Density (K) LOS: Upper LOS level	Density k (m^2/p): Plat/CC*	Queuing	Stairs
A	3.3	1.2	1.9
B	2.3	0.9	1.4
C	1.4	0.7	0.9
D	0.9	0.3	0.7
E	0.5	0.2	0.4
F	<0.5	<0.2	<0.4

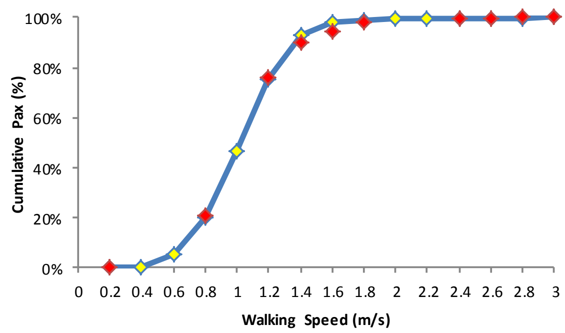
Plat = Platform; CC= Concourse

Histogram Mapping:

Stair(Down) to Platform Boarding Mapping

Platform Boarding HG: Speed (m/s)	Pax (%)	Σpax (%) (A)	Stair (Down) HG: Speed (m/s)	Pax (%)	ΣPax (%)	Allocated*: Stair Speed (m/s)	Σpax (%) (B)
0.2	0.0%	0.0%	0.2	0.0%	0.0%	0.2	0.0%
0.4	0.1%	0.1%	0.4	20.5%	20.5%	0.4	
0.6	5.3%	5.4%	0.6	55.3%	75.8%	0.4	
0.8	14.5%	19.9%	0.8	14.2%	90.0%	0.4	20.5%
1	26.9%	46.8%	1	4.6%	94.6%	0.6	
1.2	28.4%	75.2%	1.2	3.2%	97.8%	0.6	75.8%
1.4	17.5%	92.7%	1.4	1.4%	99.2%	0.8	90.0%
1.6	5.3%	98.0%	1.6	0.5%	99.7%	1	94.6%
1.8	0.9%	98.9%	1.8	0.2%	99.9%	1.2	97.8%
2	0.4%	99.3%	2	0.1%	100.0%	1.4	
2.2	0.0%	99.3%	2.2	0.0%	100.0%	1.4	
2.4	0.0%	99.3%	2.4	0.0%	100.0%	1.4	99.2%
2.6	0.1%	99.4%	2.6	0.0%	100.0%	1.6	99.7%
2.8	0.1%	99.5%	2.8	0.0%	100.0%	1.8	99.9%
3	0.5%	100.0%	3	0.0%	100.0%	2	100.0%





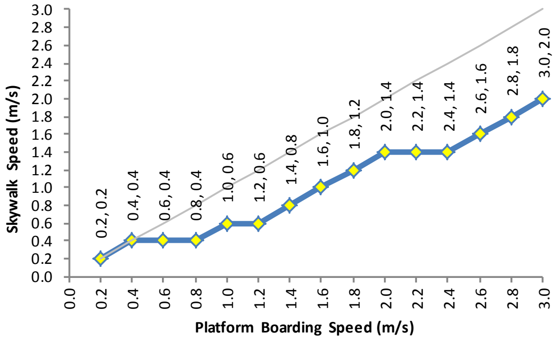
* Allocate Stair Speeds so that the highlighted cell values in Column "B" match the highlighted cell values in Column "A" as close as possible. Note: HG = Histogram

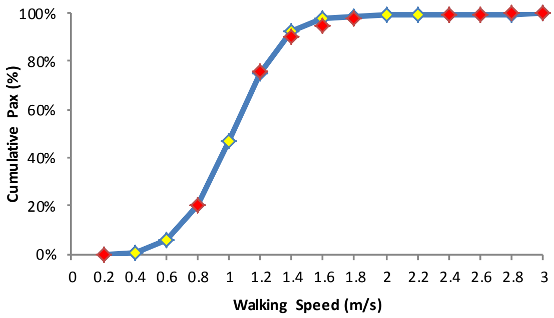
DEFAULT PARAMETERS (PAGE 3)

Histogram Mapping:

Skywalk to Platform Boarding Mapping

Platform Boarding HG			Skywalk HG			Allocated*	
Speed (m/s)	Pax (%)	Σpax (%) (A)	Speed (m/s)	Pax (%)	ΣPax (%)	Walk Speed (m/s)	Σpax (%) (B)
0.2	0.0%	0.0%	0.2	0.0%	0.0%	0.2	0.0%
0.4	0.1%	0.1%	0.4	0.0%	0.0%	0.4	
0.6	5.3%	5.4%	0.6	3.2%	3.2%	0.4	
0.8	14.5%	19.9%	0.8	11.1%	14.3%	0.4	20.5%
1	26.9%	46.8%	1	25.1%	39.4%	0.6	
1.2	28.4%	75.2%	1.2	30.5%	69.9%	0.6	75.8%
1.4	17.5%	92.7%	1.4	17.5%	87.4%	0.8	90.0%
1.6	5.3%	98.0%	1.6	6.4%	93.8%	1	94.6%
1.8	0.9%	98.9%	1.8	2.3%	96.1%	1.2	97.8%
2	0.4%	99.3%	2	1.0%	97.1%	1.4	
2.2	0.0%	99.3%	2.2	0.6%	97.7%	1.4	
2.4	0.0%	99.3%	2.4	0.5%	98.2%	1.4	99.2%
2.6	0.1%	99.4%	2.6	0.5%	98.7%	1.6	99.7%
2.8	0.1%	99.5%	2.8	0.4%	99.1%	1.8	99.9%
3	0.5%	100.0%	3	0.9%	100.0%	2	100.0%



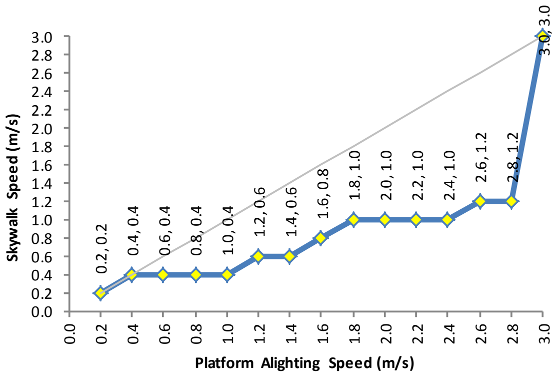


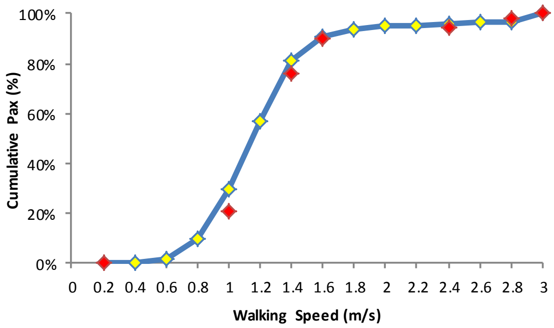
* Allocate Skywalk Speeds so that the highlighted cell values in Column "B" match the highlighted cell values in Column "A" as close as possible. Note: HG = Histogram

Histogram Mapping:

Skywalk to Platform Alighting Mapping

Platform Alighting HG			Skywalk HG			Allocated*	
Speed (m/s)	Pax (%)	Σpax (%) (A)	Speed (m/s)	Pax (%)	ΣPax (%)	Walk Speed (m/s)	Σpax (%) (B)
0.2	0.0%	0.0%	0.2	0.0%	0.0%	0.2	0.0%
0.4	0.0%	0.0%	0.4	0.0%	0.0%	0.4	
0.6	2.0%	2.0%	0.6	3.2%	3.2%	0.4	
0.8	7.9%	9.9%	0.8	11.1%	14.3%	0.4	
1	20.0%	29.9%	1	25.1%	39.4%	0.4	20.5%
1.2	27.3%	57.2%	1.2	30.5%	69.9%	0.6	
1.4	23.7%	80.9%	1.4	17.5%	87.4%	0.6	75.8%
1.6	9.5%	90.4%	1.6	6.4%	93.8%	0.8	90.0%
1.8	3.6%	94.0%	1.8	2.3%	96.1%	1	
2	0.8%	94.8%	2	1.0%	97.1%	1	
2.2	0.5%	95.3%	2.2	0.6%	97.7%	1	
2.4	0.5%	95.8%	2.4	0.5%	98.2%	1	94.6%
2.6	0.6%	96.4%	2.6	0.5%	98.7%	1.2	
2.8	0.4%	96.8%	2.8	0.4%	99.1%	1.2	97.8%
3	3.2%	100.0%	3	0.9%	100.0%	3	100.0%



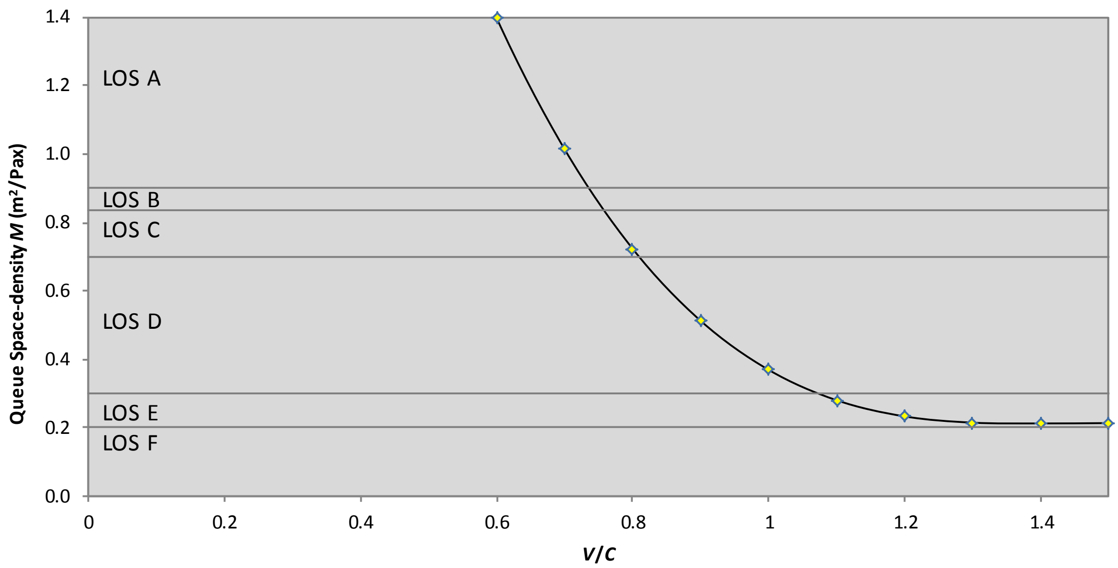


* Allocate Stair Speeds so that the highlighted cell values in Column "B" match the highlighted cell values in Column "A" as close as possible. Note: HG = Histogram

DEFAULT PARAMETERS (PAGE 4)

TVP LOS Relationship between v/c and Space-density (*M*)

$M = -2.1324 \ (v/c)^3 + 9.1192 \ (v/c)^2 + -12.9800 \ (v/c) + 6.3627$



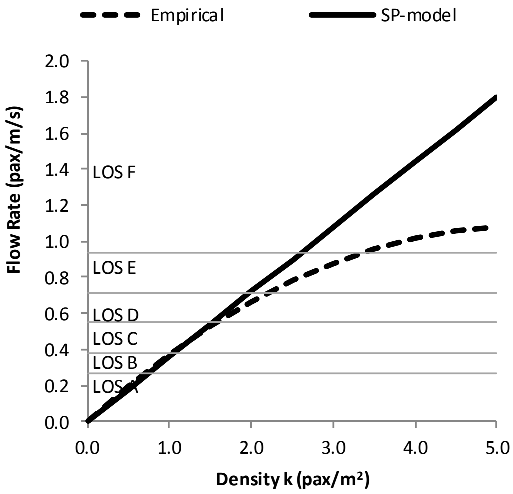
Means of Evacuation:

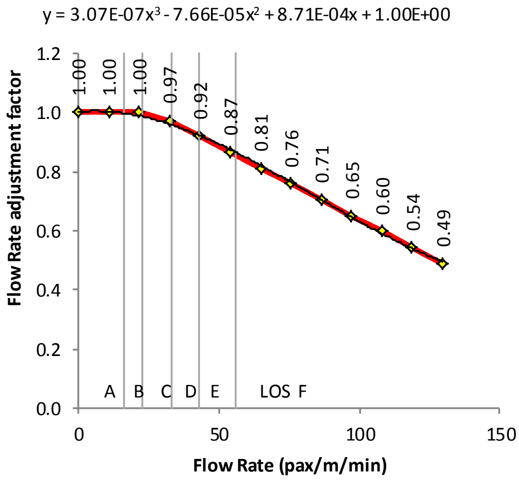
	Exit Capacity		Travel Speed		
Platforms, corridors and ramps (ends) < 4% slope:	89.4	ppm/m	61.00	m/min	
Stairs, stopped escalators and ramps > 4%: Up direction	62.6	ppm/m	15.24	m/min	(indicates vertical component of travel speed)
Stairs, stopped escalators and ramps > 4%: Down directio	71.7	ppm/m	18.30	m/min	(indicates vertical component of travel speed)
Exit Lanes, doors and gates (min 914.4mm wide):	89.4	ppm/m			

DEFAULT PARAMETERS (PAGE 5)

Staircase : Q vs K relationship adjustment factor

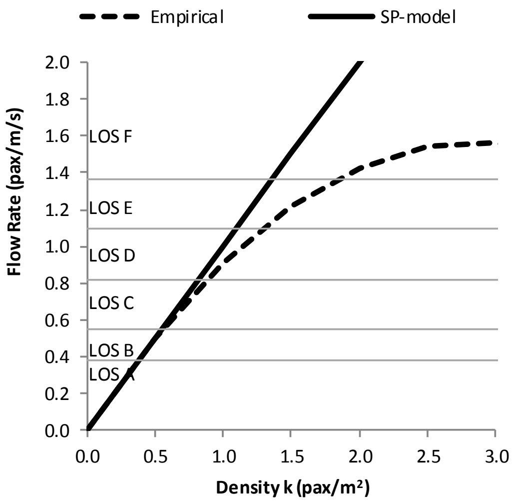
q vs k relationship :		q =	-0.0387	k^2 +	0.409	x			(Black dotted line : Left hand graph)
linear relationship :		q =	0.36	k^2 +	0				(Black line : Left hand graph)
Fr factor :	Fr =	3.07E-07	q^3 +	-7.66E-05	q^2 +	8.71E-04	q +	1.00E+00	(From trend eqn : Right graph

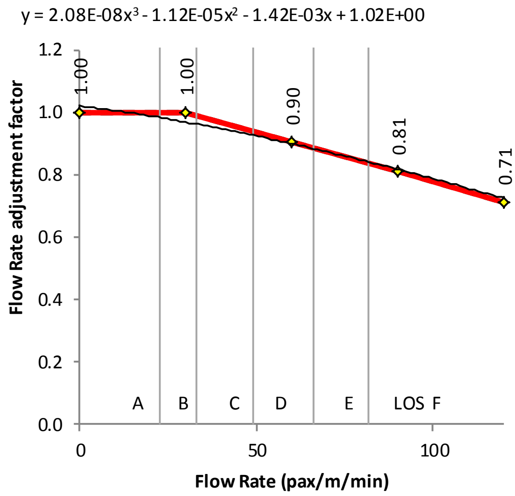




Skywalk : Q vs K relationship adjustment factor

q vs k relationship :		q =	-0.1919	k^2 +	1.0965	x			(Black dotted line : Left hand graph)
linear relationship :		q =	1	k^2 +	0				(Black line : Left hand graph)
Fr factor :	Fr =	2.08E-08	q^3 +	-1.12E-05	q^2 +	-1.42E-03	q +	1.02E+00	(From trend eqn : Right graph

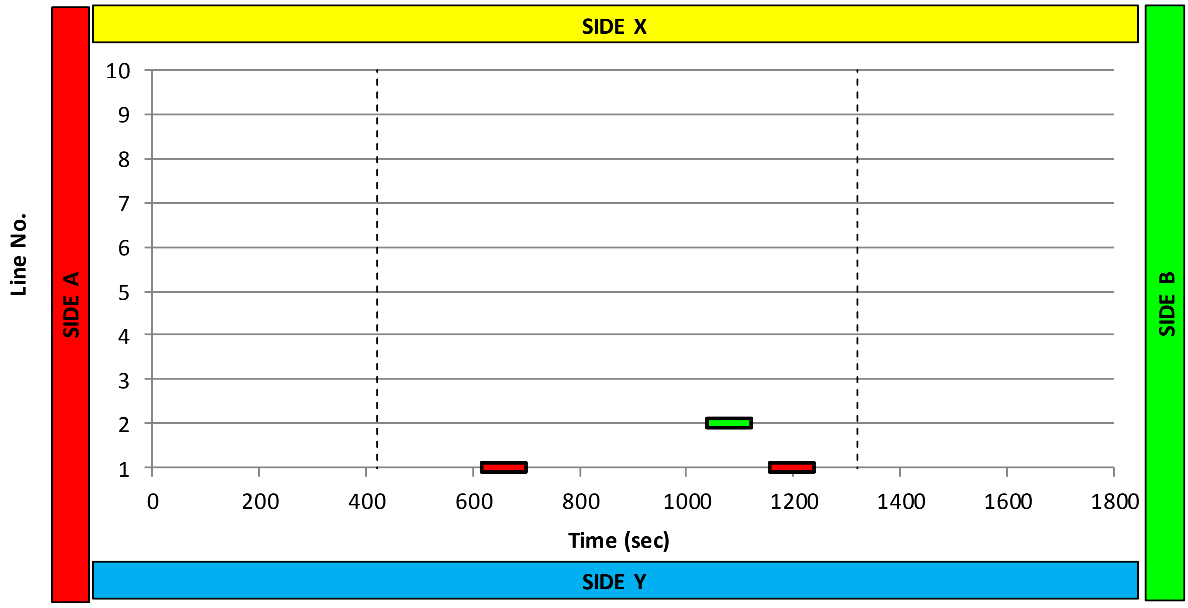




TRAIN SCHEDULE AND PASSENGER VOLUMES

Train No.	Train Type	Platform	Line No.	Train Direction	Stop Arrival time (sec)	Alighting Pax	Boarding Pax	On-board Pax	Train Length	Capacity (Pax)
1	1	1	1	towards A	660	305	195	500	229.4	2604,OK
2	1	2	2	towards B	1080	205	129	500	229.4	2604,OK
3	1	1	1	towards A	1200	118	73	500	229.4	2604,OK
4	0	0	0	n/a	0	0	0	0	0	
5	0	0	0	n/a	0	0	0	0	0	
6	0	0	0	n/a	0	0	0	0	0	
7	0	0	0	n/a	0	0	0	0	0	
8	0	0	0	n/a	0	0	0	0	0	
9	0	0	0	n/a	0	0	0	0	0	
10	0	0	0	n/a	0	0	0	0	0	
11	0	0	0	n/a	0	0	0	0	0	
12	0	0	0	n/a	0	0	0	0	0	
13	0	0	0	n/a	0	0	0	0	0	
14	0	0	0	n/a	0	0	0	0	0	
15	0	0	0	n/a	0	0	0	0	0	
16	0	0	0	n/a	0	0	0	0	0	
17	0	0	0	n/a	0	0	0	0	0	
18	0	0	0	n/a	0	0	0	0	0	
19	0	0	0	n/a	0	0	0	0	0	
20	0	0	0	n/a	0	0	0	0	0	

TRAIN SCHEDULE



1. Colour denotes train destination for trains of similar colour.

2.All lines must carry the same colour train (denoting direction).

3. Vertical lines shows extent of pk 15-min period for evacuation.

SITUATIONAL INPUT (PAGE 1)

Miscellaneous Details:

Name of Analyst: L. Hermant
Station Name: Windermere
Assessment Period: Scenario 3.2: AM (2025)
Date of Analysis: 01 March 2011

Station Layout Details:

Platform length, PL (m): 265.00
TVP_d (m): 127.88
Platform to Concourse height (m): 5.64
Platform MAL (m): 265.00

Platform Stair Details:

Platform No. (n):	1	2	3	4	5	6
Width/stair $S(n)_w$ (m)	2.00	2.00	0.00	0.00	0.00	0.00
$S1_t$ (m):	139.72	139.72	0.00	0.00	0.00	0.00
$S1_b$ (m):	148.55	148.55	0.00	0.00	0.00	0.00
$S2_t$ (m):	135.64	135.64	0.00	0.00	0.00	0.00
$S2_b$ (m):	126.80	126.80	0.00	0.00	0.00	0.00
$S3_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S3_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform offset $P(n)_d$ (m):	8.16	8.16	0.00	0.00	0.00	0.00
Platform width, Pw(n) (m):	6.00	9.00	0.00	0.00	0.00	0.00
Eff.Platform width,EPW (m):	3.10	3.10	0.00	0.00	0.00	0.00

Concourse Details:

Concourse width (m): 16.10
Concourse length to TVP's (m): 18.07
Total No. of TVP/Turnstiles: 4 (TVP: Ticket Verification Point)
Turnstile capacity (pax/min): 30 (Note: Capacity is capacity per turnstile)
Turnstile unit width (TUW) (m): 0.9 OK, Total TUW < Concourse width
Turnstile evac capacity (pax/min): 50 (evac: Evacuation capacity per turnstile)
No. Escape Gates: 1 (alongside TVP Battery)
Width of Escape Gates (m) : 1.43
No. Bypass Gates: 1 (alongside TVP Battery)
Width of Bypass Gates (m) : 0.92

Skywalk Details:

Skywalk width on Side X (m):	4.20	Skywalk width on Side Y (m):	4.20	Name Side X: CENTURY CITY
% of Pax Boarding from Side X:	25.0%	% of Pax Boarding from Side Y:	75.0%	Name Side Y: KENSINGTON
% of Pax Alighting to Side X:	100.0%	% of Pax Alighting to Side Y:	0.0%	
Flow rate evaluation dist (Fred) (m):	10.50			
Ave. Street-to-Street Pax volume:	18	pax/min		

SITUATIONAL INPUT (PAGE 2)

Platform Emergency Details:

Platform No.:	1	2	3	4	5	6
No. Emergency Stairs:	0	0	0	0	0	0
Width/emergency stair (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of emergency stairs (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform ramp ends avail. for escape:	None	None	None	None	None	None
Width/Platform ramp end (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of platform ramp-ends (m):	0.00	0.00	0.00	0.00	0.00	0.00
No. Side Platform exit gates:	3	3	0	0	0	0
Width/Side Platform exit gate (m):	2.00	2.00	0.00	0.00	0.00	0.00
Effective width of side platform gates (m):	6.00	6.00	0.00	0.00	0.00	0.00

Foyer Details:

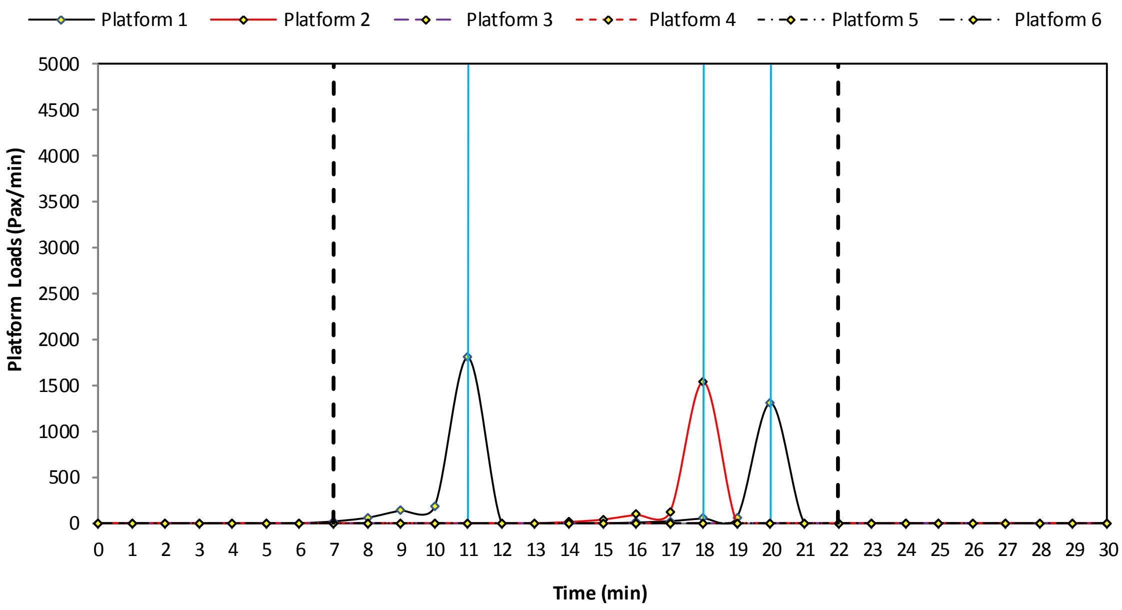
Foyer width (m):	8.85	
Foyer length to TVP's (m):	11.20	
Eff. Foyer Entrance width (m):	8.28	
No. Escape Gates:	1	(alongside Foyer Entrance)
Width of Escape Gates (m) :	1.00	
No. Bypass Gates:	0	(alongside Foyer Entrance)
Width of Bypass Gates (m) :	0.00	

Comments:

1	Street to street volumes: 14ppm in 2015 and 18ppm in 2025. (Goba, 2009:16)
2	Stair riser = 174mm and tread = 275mm. Hoz length therefore = 8.91m from platform to concourse.
3	Street-to-street volumes excluded from Scenatio 1
4	Empty
5	Empty
6	Empty
7	Empty
8	Empty
9	Empty
10	Empty

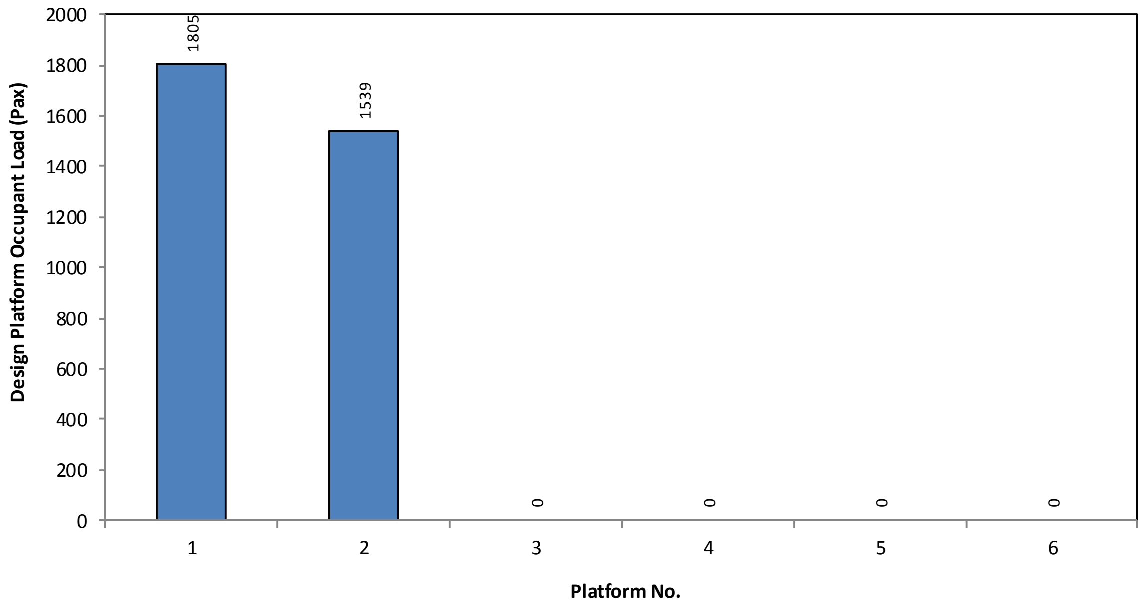
EVACUATION: LONGITUDINAL PLATFORM LOADS

Platform Loads per minute:



1. Vertical dotted lines represent extent of peak 15-min period for evacuation calculations

EVACUATION: PLATFORM OCCUPANT LOADS



Platform :	1	2	3	4	5	6	Total
Platform Occupant Load :	1805	1539	0	0	0	0	3344

EVACUATION: NFPA 130 EXITING ANALYSIS

Element	Direction	No. Units	Eff. Width (m)	Unit Capacity (pax/m/min)	Unit Capacity (pax/min)
Platform to Concourse (via Stairs)					
Stairs	Up	4	4.00	62.6	250
	Down	0	0	71.7	0
Escalators	Up	0	0	62.6	0
	Down	0	0	71.7	0
Emergency Stairs	Up	0	0.00	62.6	0
	Down	0	0	71.7	0
Platform Ramp Ends	Down	0	0.00	89.4	0
Platform Side Gates	On Side Platforms only	6	12.00	89.4	1073
				Total	1323
Concourse to Foyer (through TVP battery)					
Turnstiles		4	0.90	25	100
TVP Escape gates		1	1.43	89.4	128
TVP Bypass gates		1	0.92	89.4	82
				Total	310
Foyer to Safe Area (through Foyer Entrance gates)					
Foyer Entrance gates			8.28	89.4	740
Foyer Escape gates		1	1	89.4	89
Foyer Bypass gates		0	0	89.4	0
				Total	830

Walking Time for Longest Exit Route		Distance (m)	Walk Speed (m/min)	Minutes
Platform to Safe Area				
On Platform	T_1	148.55	61.00	2.44
Platform to Concourse (via stairs)*	T_2	5.64	15.24	0.37
On Concourse and foyer	T_3	29.66	61.00	0.49
Concourse to grade (via stairs)	T_4	0	71.7	0.00
On grade to safe area (via skywalk)	T_5	0.75	61.00	0.01
**: Distance is vertical distance*		T (total walking time) = $T_1 + T_2 + T_3 + T_4 + T_5$ =		3.30

Test No. 1: Evacuate platform occupant load(s) from platform(s) in 4 minutes or less.

W_1 (time to clear platform) = $\frac{\text{Platform occupant load}}{\text{Platform exit capacity}} = \frac{3344}{1323}$ = 2.53 minutes **<4 min, OK**

Test No. 2: Evacuate platform occupant load(s) from most remote point on platform to a point of safety in 6 minutes or less.

W_p (waiting time at platform exits) = $W_1 - T_1$ = 0.09 minutes

Concourse occupant load = Platform occupant load - (W_1 x platform emergency exit capacity) = 633 persons

W_2 (TVP flow time) = $\frac{\text{Concourse occupant load}}{\text{TVP exit capacity}} = \frac{633}{310}$ = 2.04 minutes

W_f (waiting time at TVP's) = $W_2 - T_1$ = 0.00 minutes

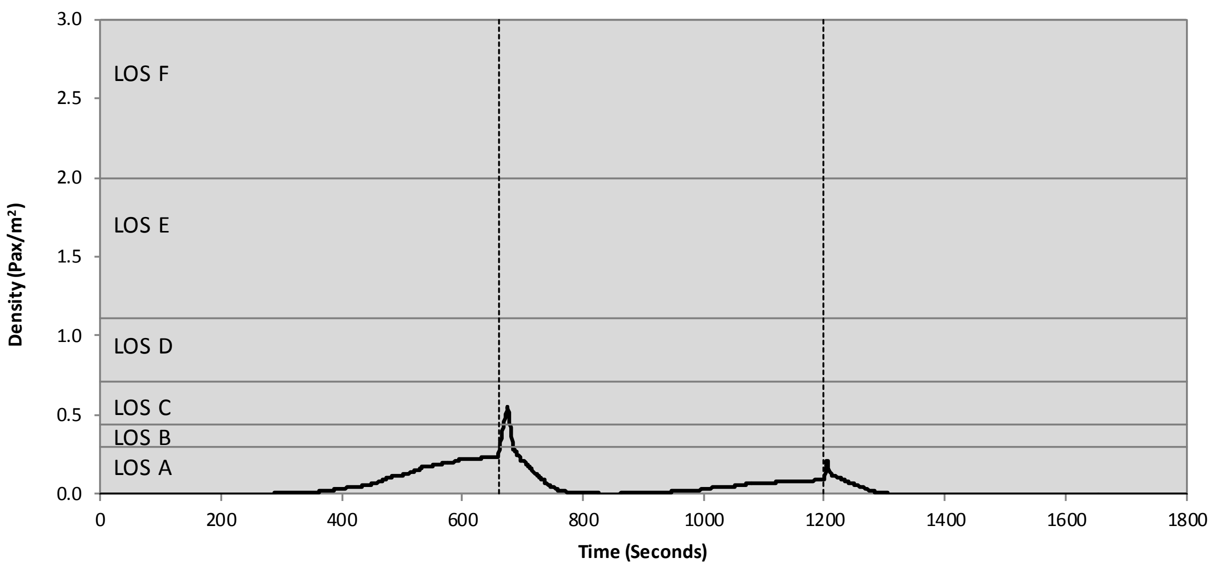
W_3 (Foyer exit flow time) = $\frac{\text{Concourse occupant load}}{\text{Foyer exit capacity}} = \frac{633}{830}$ = 0.76 minutes

W_c (waiting time at foyer exit) = W_3 - max (W_2 or W_1) = 0.00 minutes

Total exit time = $T + W_p + W_f + W_c$ = 3.40 minutes **<6 min, OK**

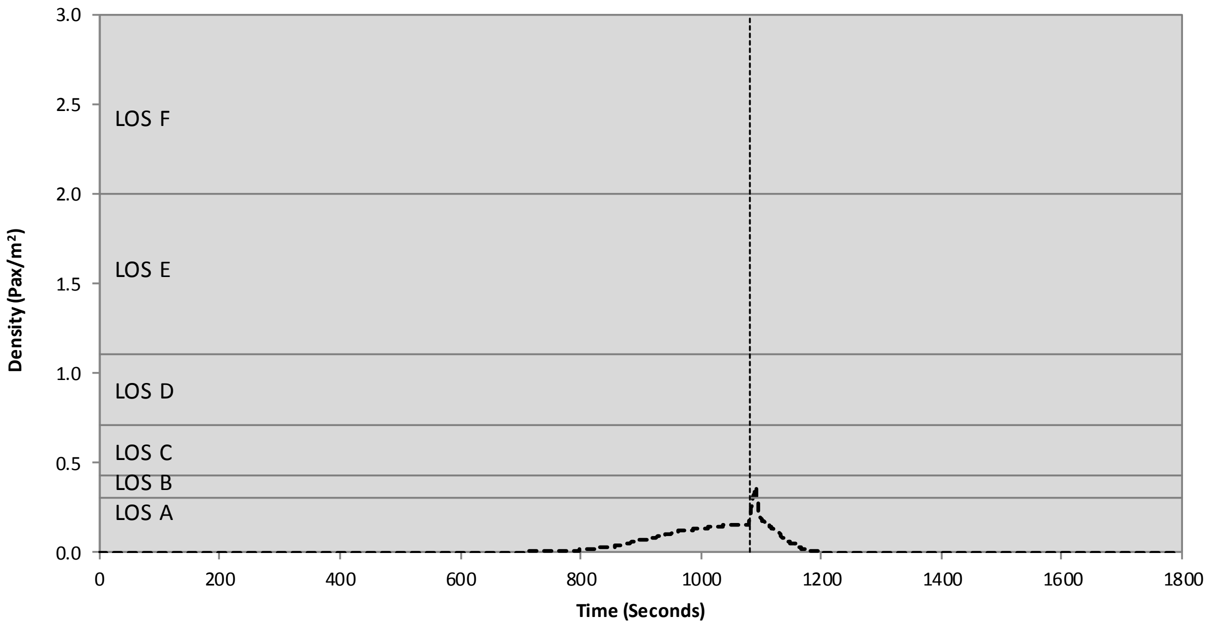
PLATFORM DENSITY PLOTS

Plot 1: Platform 1



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1779	10	11	0	0	0
Total Time in %:	98.8%	0.6%	0.6%	0.0%	0.0%	0.0%

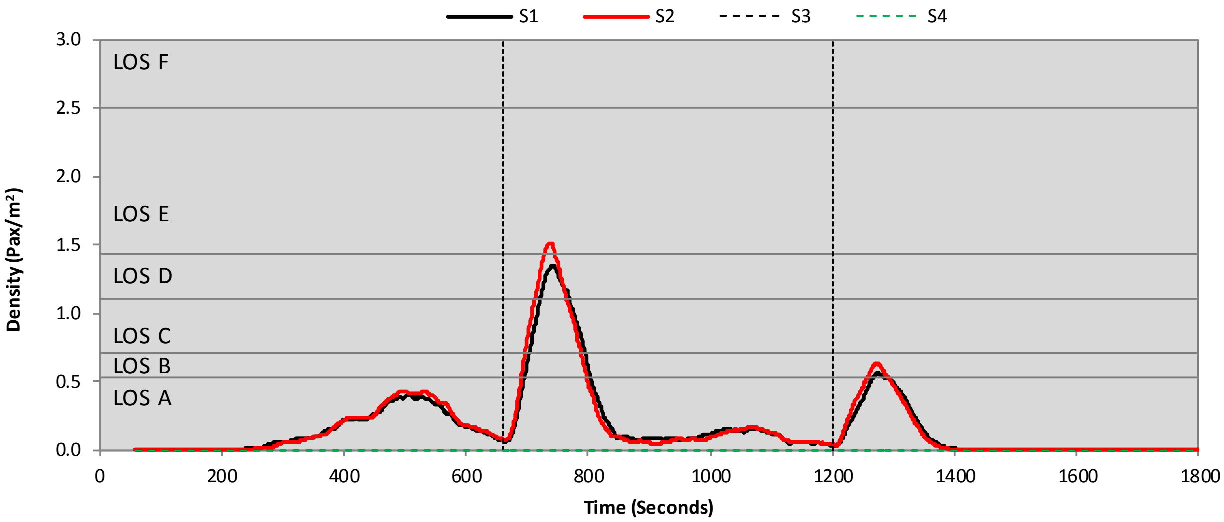
Plot 2: Platform 2



Total Time in sec:	1793	7	0	0	0	0
Total Time in %:	99.6%	0.4%	0.0%	0.0%	0.0%	0.0%

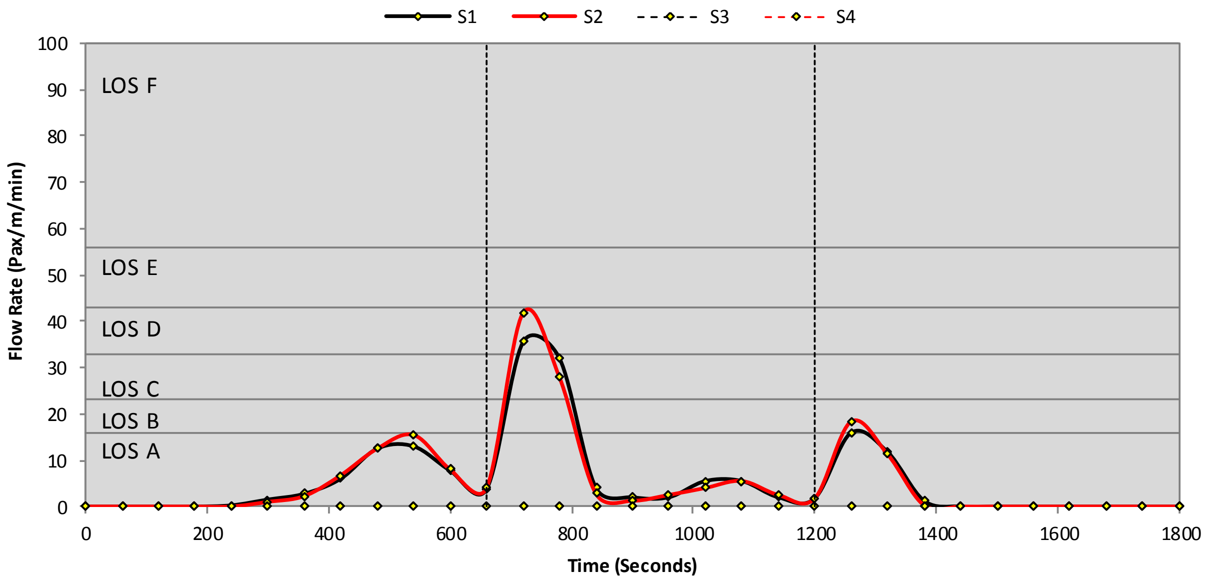
STAIR DENSITY PLOT (over length of stairs)

Plot 1: Platform 1



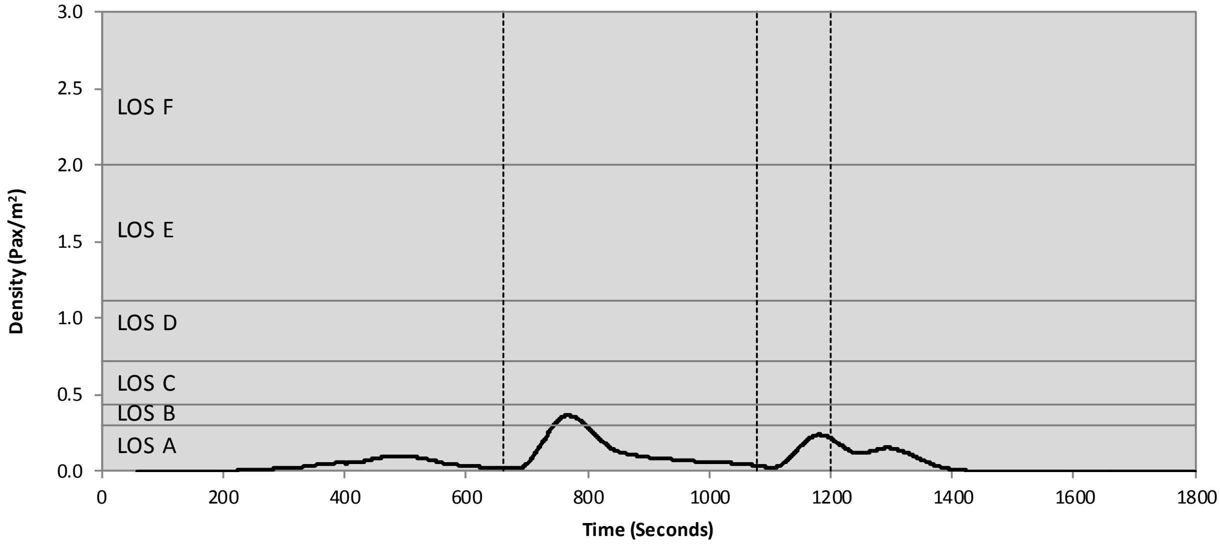
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	1611 (92.5%)	40 (2.3%)	44 (2.5%)	47 (2.7%)	0 (0%)	0 (0%)
S2 : Total Time s (%)	1600 (91.8%)	51 (2.9%)	40 (2.3%)	34 (2%)	17 (1%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

STAIR FLOW RATE PLOT (at centre of stairs)



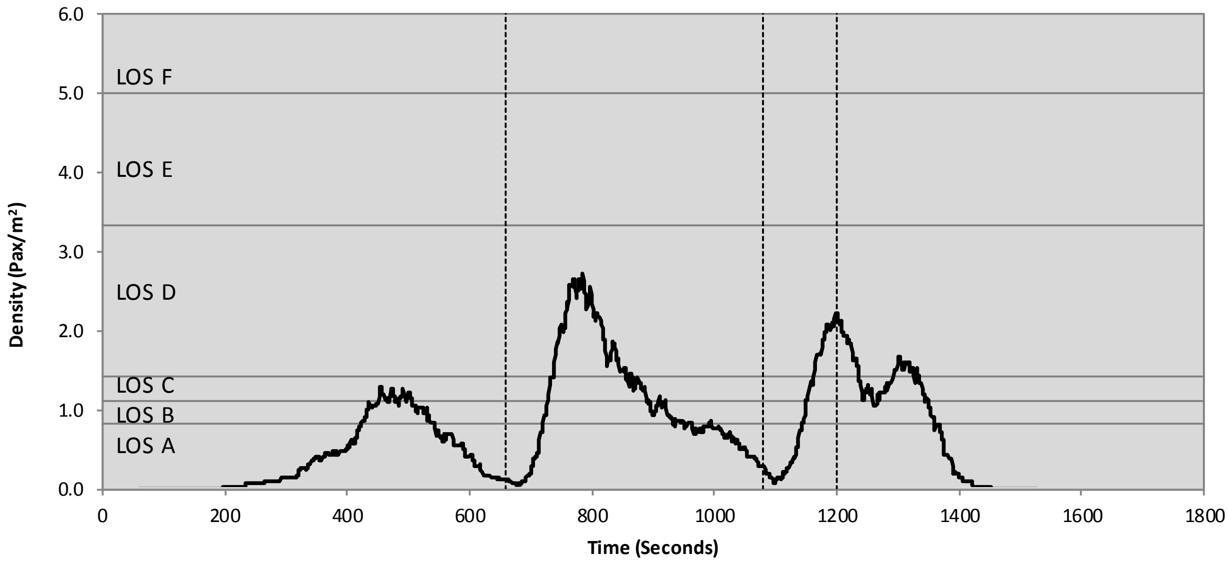
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	28 (93.3%)	0 (0%)	1 (3.3%)	1 (3.3%)	0 (0%)	0 (0%)
S2 : Total Time s (%)	27 (90%)	1 (3.3%)	1 (3.3%)	1 (3.3%)	0 (0%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

CONCOURSE DENSITY PLOT



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1748	52	0	0	0	0
Total Time in %:	97.1%	2.9%	0.0%	0.0%	0.0%	0.0%

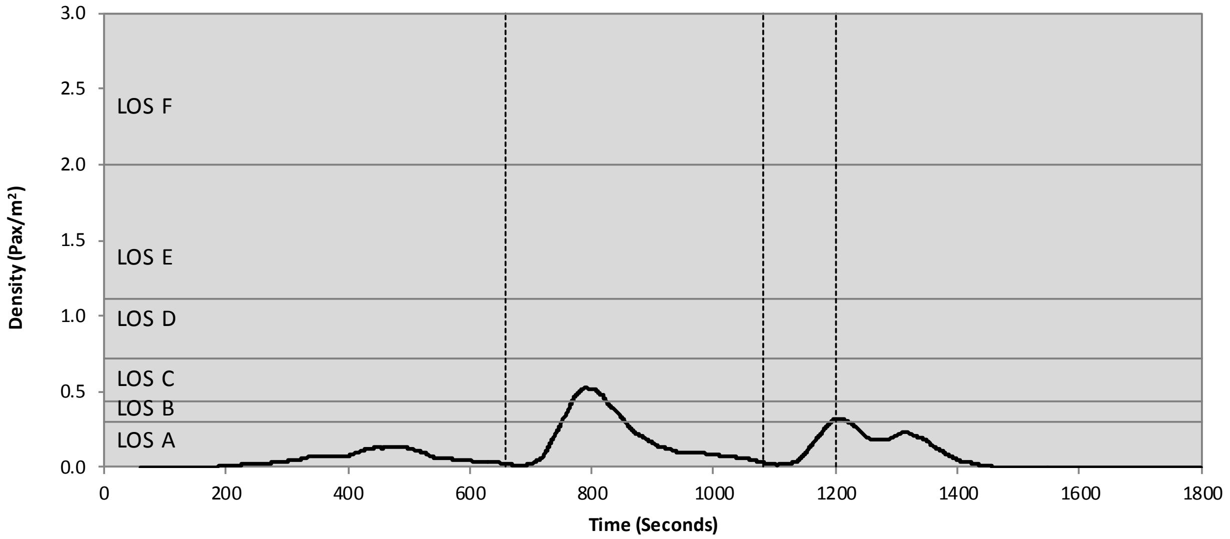
TVP QUEUE DENSITY PLOT



Total No. of TVP/Turnstiles: 4 Turnstile capacity (pax/min): 30

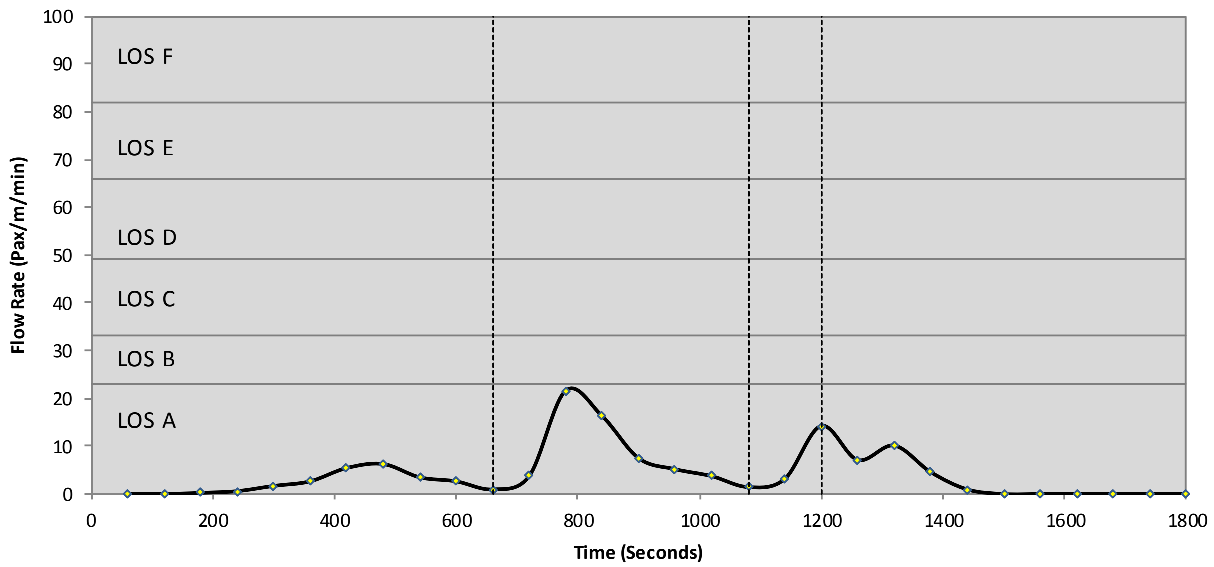
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec	1173	165	171	232	0	0
Total Time in %:	67.4%	9.5%	9.8%	13.3%	0.0%	0.0%

FOYER DENSITY PLOT



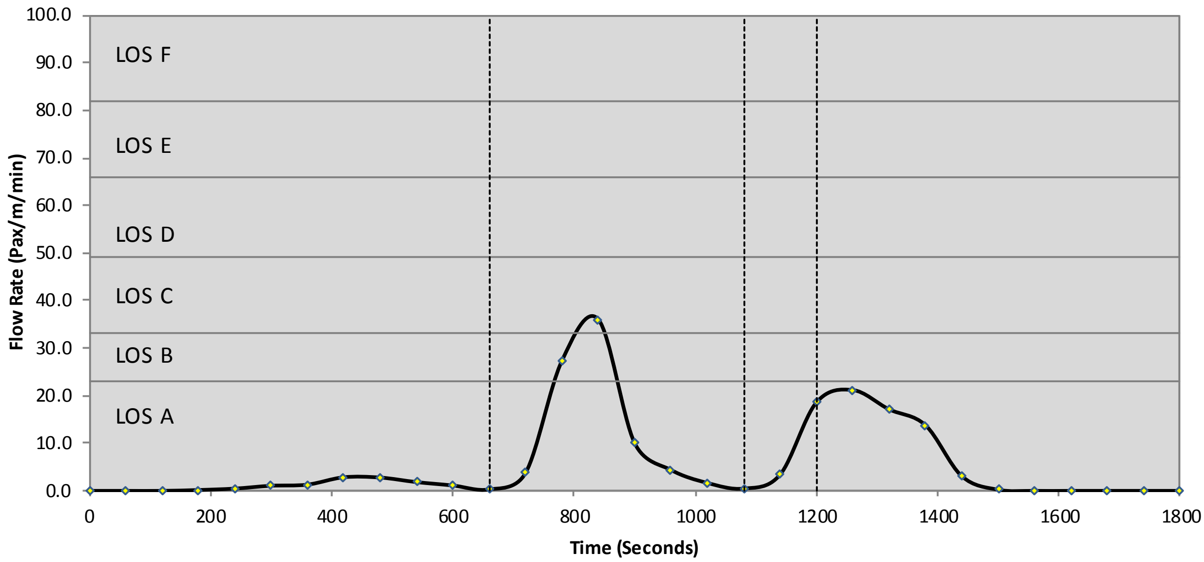
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1669	73	58	0	0	0
Total Time in %:	92.7%	4.1%	3.2%	0.0%	0.0%	0.0%

FOYER ENTRANCE FLOW RATE PLOT



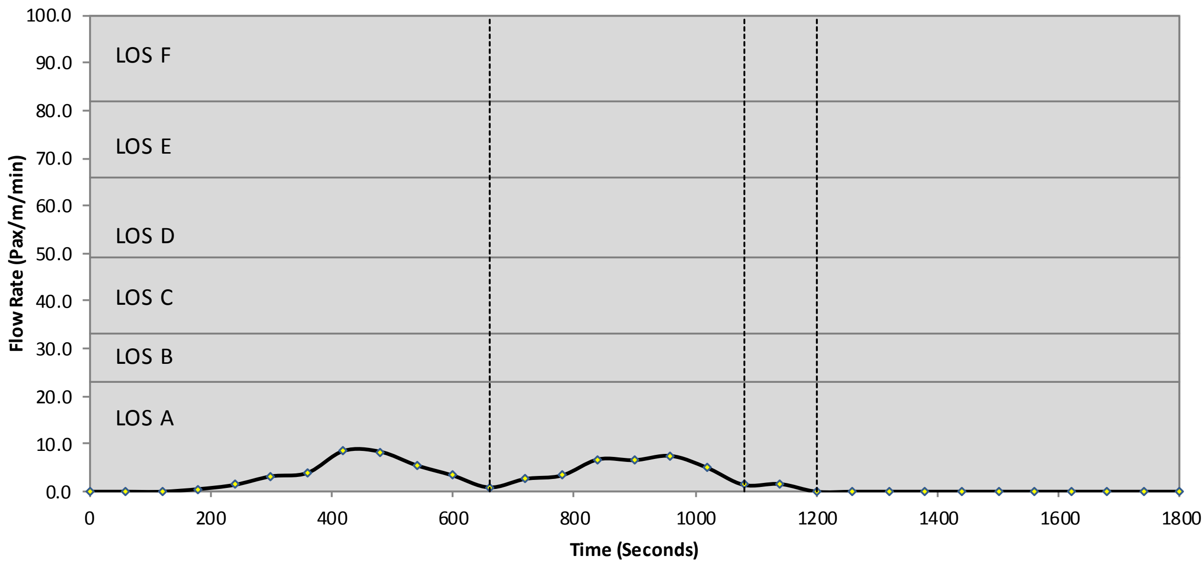
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	30	0	0	0	0	0
Total Time in %:	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE X): CENTURY CITY SIDE



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1680	60	60	0	0	0
Total Time in %:	93.3%	3.3%	3.3%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE Y): KENSINGTON SIDE



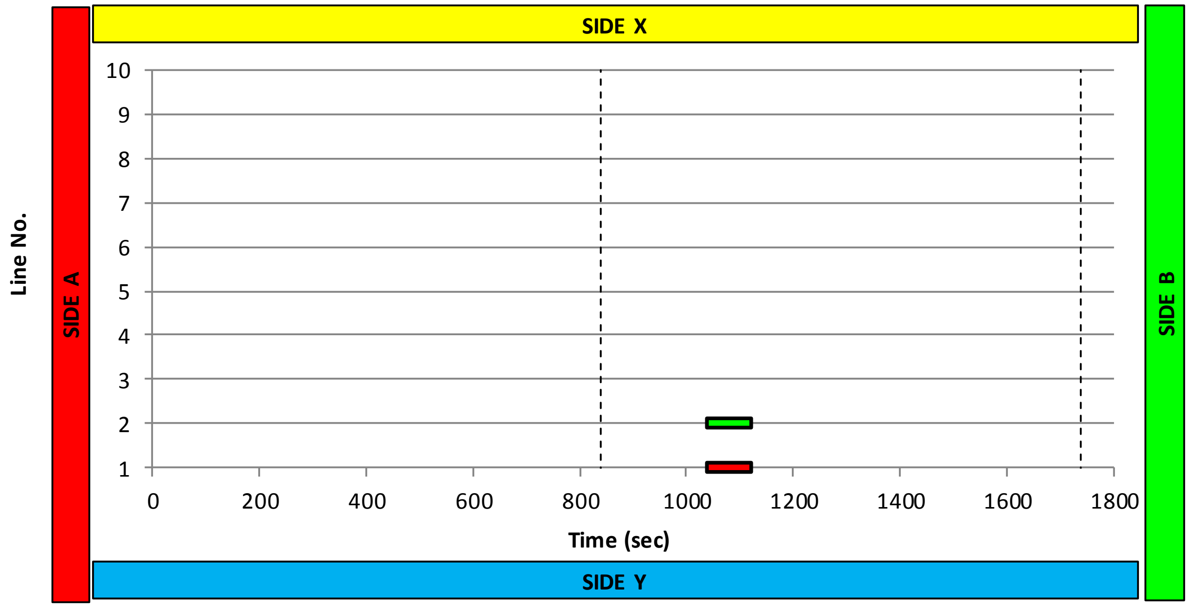
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1800	0	0	0	0	0
Total Time in %:	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

24. APPENDIX N: SP-MODEL OUTPUTS: CENTURY CITY STATION (SCENARIO 2)

TRAIN SCHEDULE AND PASSENGER VOLUMES

Train No.	Train Type	Platform	Line No.	Train Direction	Stop Arrival time (sec)	Alighting Pax	Boarding Pax	On-board Pax	Train Length	Capacity (Pax)
1	1	1	1	towards A	1080	235	148	500	229.4	2604,OK
2	1	2	2	towards B	1080	235	148	500	229.4	2604,OK
3	0	0	0	n/a	0	0	0	0	0	
4	0	0	0	n/a	0	0	0	0	0	
5	0	0	0	n/a	0	0	0	0	0	
6	0	0	0	n/a	0	0	0	0	0	
7	0	0	0	n/a	0	0	0	0	0	
8	0	0	0	n/a	0	0	0	0	0	
9	0	0	0	n/a	0	0	0	0	0	
10	0	0	0	n/a	0	0	0	0	0	
11	0	0	0	n/a	0	0	0	0	0	
12	0	0	0	n/a	0	0	0	0	0	
13	0	0	0	n/a	0	0	0	0	0	
14	0	0	0	n/a	0	0	0	0	0	
15	0	0	0	n/a	0	0	0	0	0	
16	0	0	0	n/a	0	0	0	0	0	
17	0	0	0	n/a	0	0	0	0	0	
18	0	0	0	n/a	0	0	0	0	0	
19	0	0	0	n/a	0	0	0	0	0	
20	0	0	0	n/a	0	0	0	0	0	

TRAIN SCHEDULE



1. Colour denotes train destination for trains of similar colour.

2.All lines must carry the same colour train (denoting direction).

3. Vertical lines shows extent of pk 15-min period for evacuation.

SITUATIONAL INPUT (PAGE 1)

Miscellaneous Details:

Name of Analyst:	L. Hermant
Station Name:	Windermere
Assessment Period:	Scenario 3.2: AM (2025)
Date of Analysis:	01 March 2011

Station Layout Details:

Platform length, PL (m):	265.00
TVP_d (m):	127.88
Platform to Concourse height (m):	5.64
Platform MAL (m):	265.00

Platform Stair Details:

Platform No. (n):	1	2	3	4	5	6
Width/stair $S(n)_w$ (m)	2.00	2.00	0.00	0.00	0.00	0.00
$S1_t$ (m):	139.72	139.72	0.00	0.00	0.00	0.00
$S1_b$ (m):	148.55	148.55	0.00	0.00	0.00	0.00
$S2_t$ (m):	135.64	135.64	0.00	0.00	0.00	0.00
$S2_b$ (m):	126.80	126.80	0.00	0.00	0.00	0.00
$S3_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S3_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform offset $P(n)_d$ (m):	8.16	8.16	0.00	0.00	0.00	0.00
Platform width, Pw(n) (m):	6.00	9.00	0.00	0.00	0.00	0.00
Eff.Platform width,EPW (m):	3.10	3.10	0.00	0.00	0.00	0.00

Concourse Details:

Concourse width (m):	16.10	
Concourse length to TVP's (m):	18.07	
Total No. of TVP/Turnstiles:	4	(TVP: Ticket Verification Point)
Turnstile capacity (pax/min):	30	(Note: Capacity is capacity per turnstile)
Turnstile unit width (TUW) (m):	0.9	OK, Total TUW < Concourse width
Turnstile evac capacity (pax/min):	50	(evac: Evacuation capacity per turnstile)
No. Escape Gates:	1	(alongside TVP Battery)
Width of Escape Gates (m) :	1.43	
No. Bypass Gates:	1	(alongside TVP Battery)
Width of Bypass Gates (m) :	0.92	

Skywalk Details:

Skywalk width on Side X (m):	4.20	Skywalk width on Side Y (m):	4.20	Name Side X: CENTURY CITY
% of Pax Boarding from Side X:	25.0%	% of Pax Boarding from Side Y:	75.0%	Name Side Y: KENSINGTON
% of Pax Alighting to Side X:	100.0%	% of Pax Alighting to Side Y:	0.0%	
Flow rate evaluation dist (Fred) (m):	10.50			
Ave. Street-to-Street Pax volume:	18	pax/min		

SITUATIONAL INPUT (PAGE 2)

Platform Emergency Details:

Platform No.:	1	2	3	4	5	6
No. Emergency Stairs:	0	0	0	0	0	0
Width/emergency stair (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of emergency stairs (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform ramp ends avail. for escape:	None	None	None	None	None	None
Width/Platform ramp end (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of platform ramp-ends (m):	0.00	0.00	0.00	0.00	0.00	0.00
No. Side Platform exit gates:	3	3	0	0	0	0
Width/Side Platform exit gate (m):	2.00	2.00	0.00	0.00	0.00	0.00
Effective width of side platform gates (m):	6.00	6.00	0.00	0.00	0.00	0.00

Foyer Details:

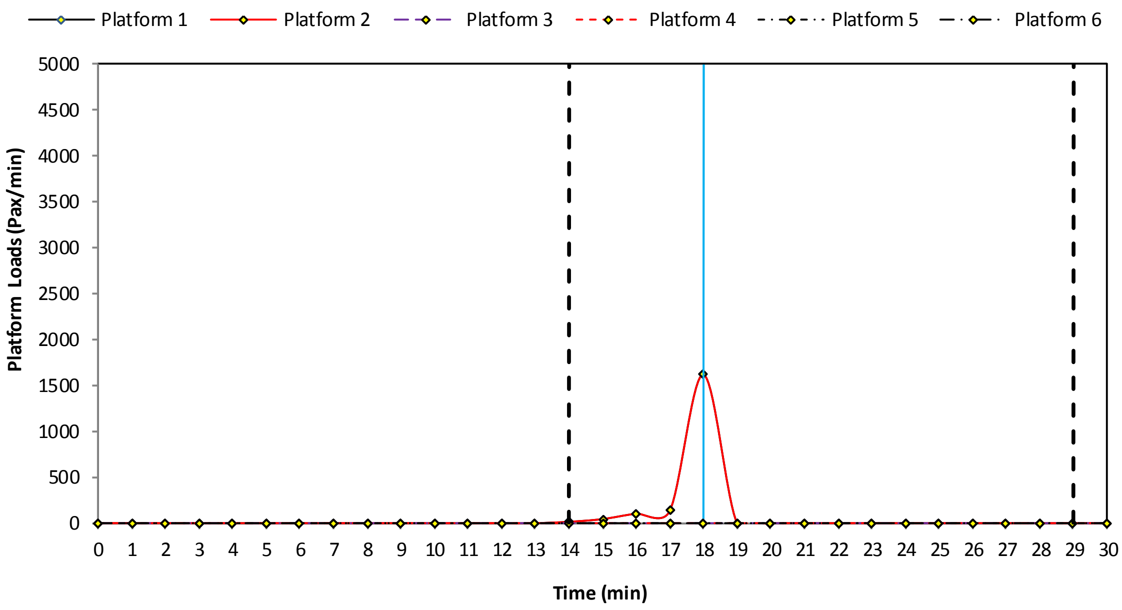
Foyer width (m):	8.85	
Foyer length to TVP's (m):	11.20	
Eff. Foyer Entrance width (m):	8.28	
No. Escape Gates:	1	(alongside Foyer Entrance)
Width of Escape Gates (m) :	1.00	
No. Bypass Gates:	0	(alongside Foyer Entrance)
Width of Bypass Gates (m) :	0.00	

Comments:

1 Street to street volumes: 14ppm in 2015 and 18ppm in 2025. (Goba, 2009:16)
2 Stair riser = 174mm and tread = 275mm. Hoz length therefore = 8.91m from platform to concourse.
3 Street-to-street volumes excluded from Scenatio 1
4 Empty
5 Empty
6 Empty
7 Empty
8 Empty
9 Empty
10 Empty

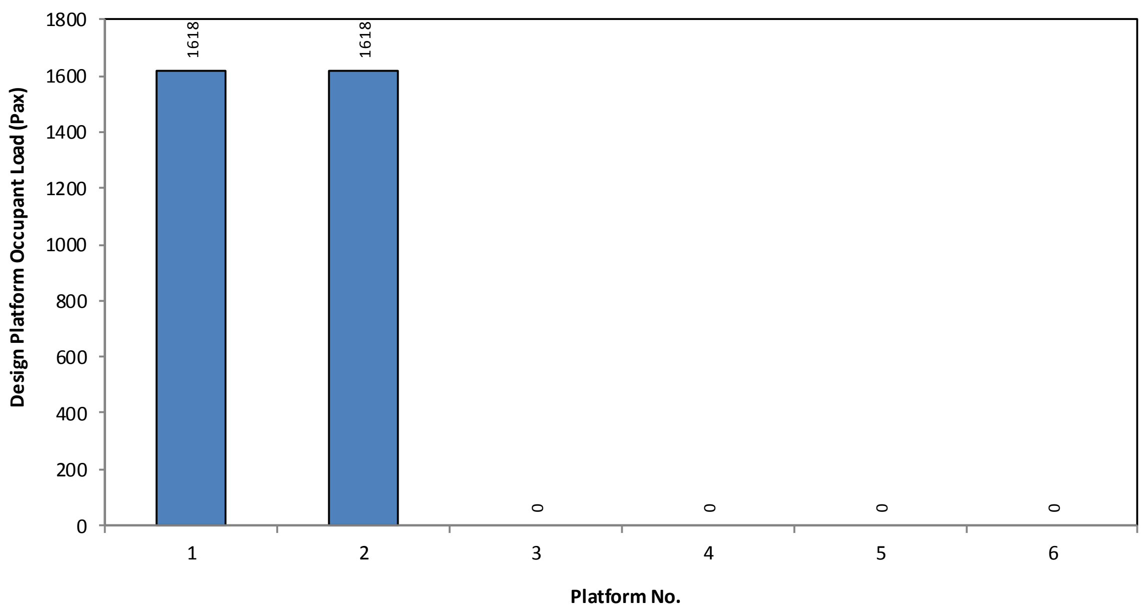
EVACUATION: LONGITUDINAL PLATFORM LOADS

Platform Loads per minute:



1. Vertical dotted lines represent extent of peak 15-min period for evacuation calculations

EVACUATION: PLATFORM OCCUPANT LOADS



Platform :	1	2	3	4	5	6	Total
Platform Occupant Load :	1618	1618	0	0	0	0	3236

EVACUATION: NFPA 130 EXITING ANALYSIS

Element	Direction	No. Units	Eff. Width (m)	Unit Capacity (pax/m/min)	Unit Capacity (pax/min)
Platform to Concourse (via Stairs)					
Stairs	Up	4	4.00	62.6	250
	Down	0	0	71.7	0
Escalators	Up	0	0	62.6	0
	Down	0	0	71.7	0
Emergency Stairs	Up	0	0.00	62.6	0
	Down	0	0	71.7	0
Platform Ramp Ends	Down	0	0.00	89.4	0
Platform Side Gates	On Side Platforms only	6	12.00	89.4	1073
				Total	1323
Concourse to Foyer (through TVP battery)					
Turnstiles		4	0.90	50	200
TVP Escape gates		1	1.43	89.4	128
TVP Bypass gates		1	0.92	89.4	82
				Total	410
Foyer to Safe Area (through Foyer Entrance gates)					
Foyer Entrance gates			8.28	89.4	740
Foyer Escape gates		1	1	89.4	89
Foyer Bypass gates		0	0	89.4	0
				Total	830

Walking Time for Longest Exit Route		Distance (m)	Walk Speed (m/min)	Minutes
Platform to Safe Area				
On Platform	T_1	148.55	61.00	2.44
Platform to Concourse (via stairs)*	T_2	5.64	15.24	0.37
On Concourse and foyer	T_3	29.66	61.00	0.49
Concourse to grade (via stairs)	T_4	0	71.7	0.00
On grade to safe area (via skywalk)	T_5	0.75	61.00	0.01
**: Distance is vertical distance*			T (total walking time) = $T_1 + T_2 + T_3 + T_4 + T_5$ =	3.30

Test No. 1: Evacuate platform occupant load(s) from platform(s) in 4 minutes or less.

W_1 (time to clear platform) = $\frac{\text{Platform occupant load}}{\text{Platform exit capacity}} = \frac{3236}{1323}$ = 2.45 minutes **<4 min, OK**

Test No. 2: Evacuate platform occupant load(s) from most remote point on platform to a point of safety in 6 minutes or less.

W_p (waiting time at platform exits) = $W_1 - T_1$ = 0.01 minutes

Concourse occupant load = Platform occupant load - (W_1 x platform emergency exit capacity) = 612 persons

W_2 (TVP flow time) = $\frac{\text{Concourse occupant load}}{\text{TVP exit capacity}} = \frac{612}{410}$ = 1.49 minutes

W_f (waiting time at TVP's) = $W_2 - T_1$ = 0.00 minutes

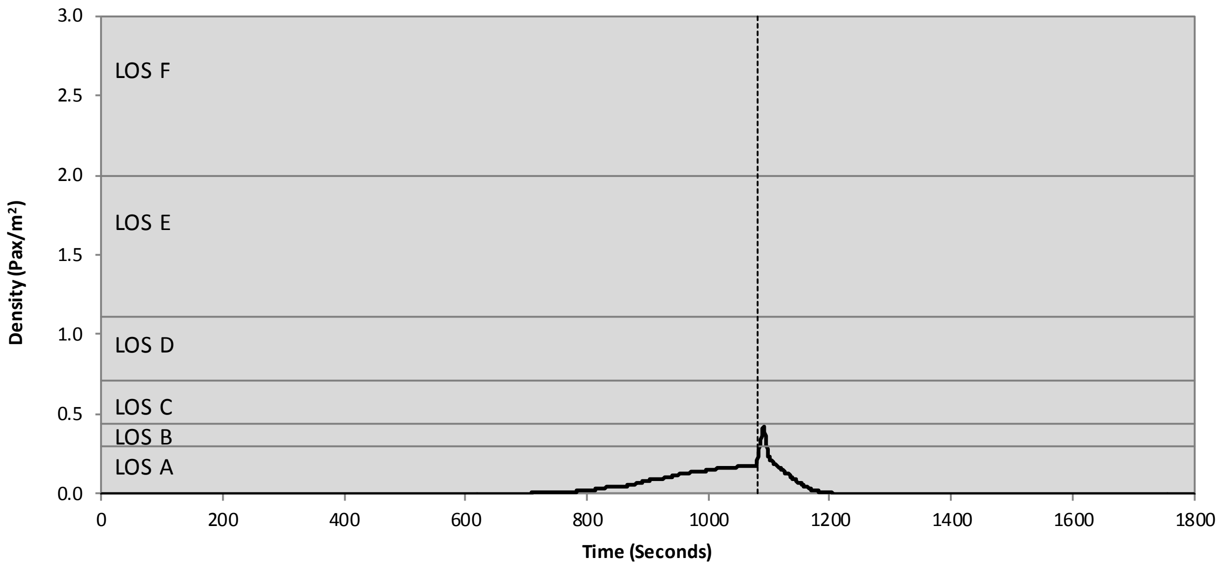
W_3 (Foyer exit flow time) = $\frac{\text{Concourse occupant load}}{\text{Foyer exit capacity}} = \frac{612}{830}$ = 0.74 minutes

W_c (waiting time at foyer exit) = W_3 - max (W_2 or W_1) = 0.00 minutes

Total exit time = $T + W_p + W_f + W_c$ = 3.31 minutes **<6 min, OK**

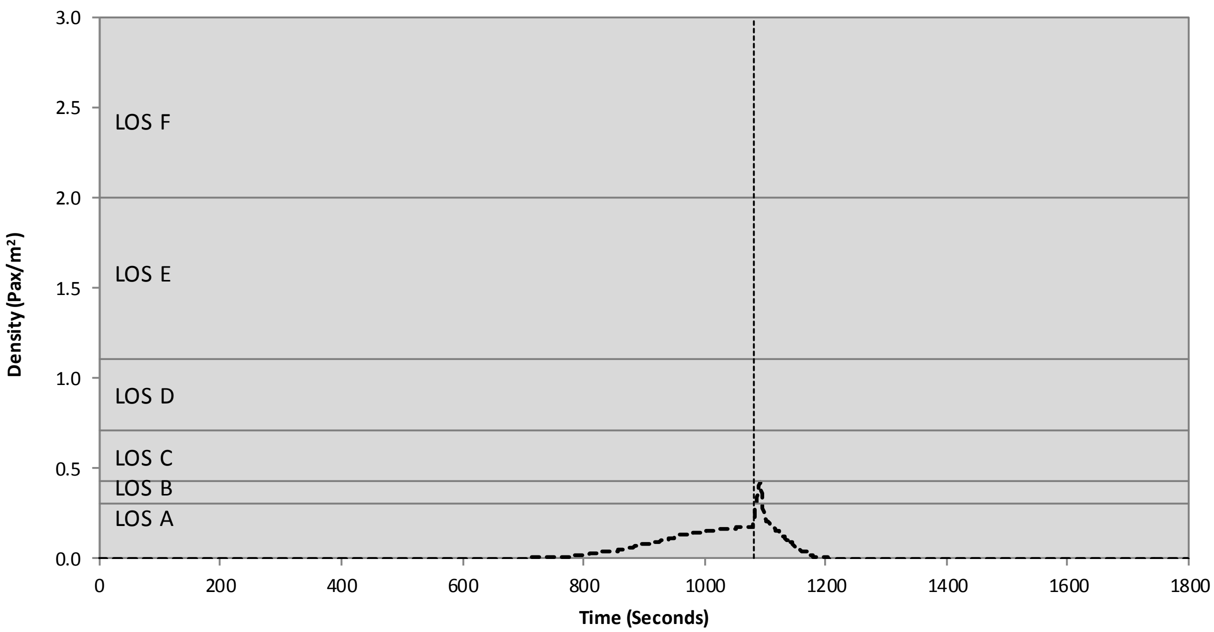
PLATFORM DENSITY PLOTS

Plot 1: Platform 1



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1789	11	0	0	0	0
Total Time in %:	99.4%	0.6%	0.0%	0.0%	0.0%	0.0%

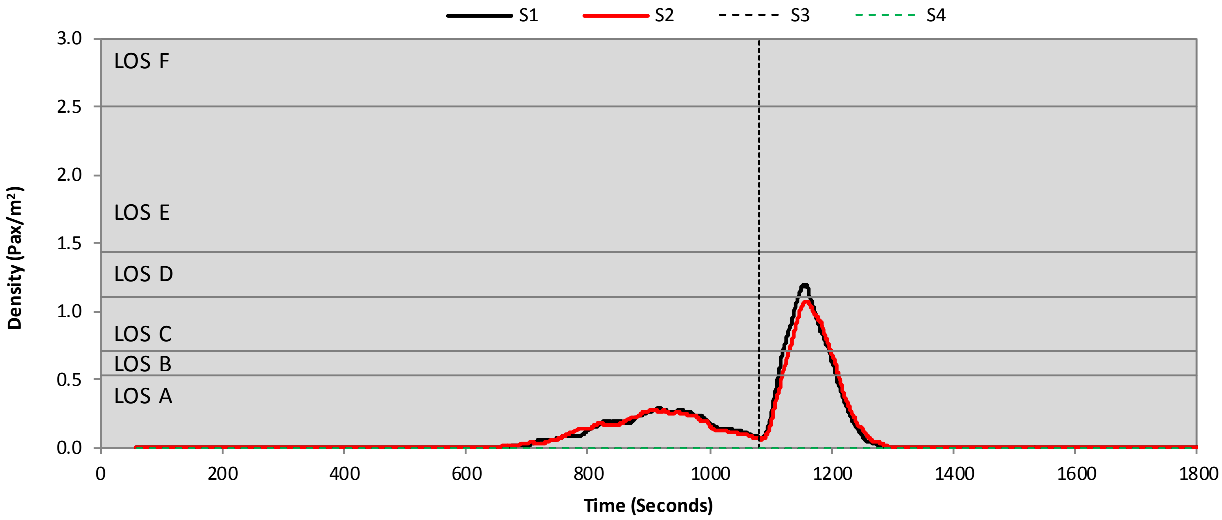
Plot 2: Platform 2



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1789	11	0	0	0	0
Total Time in %:	99.4%	0.6%	0.0%	0.0%	0.0%	0.0%

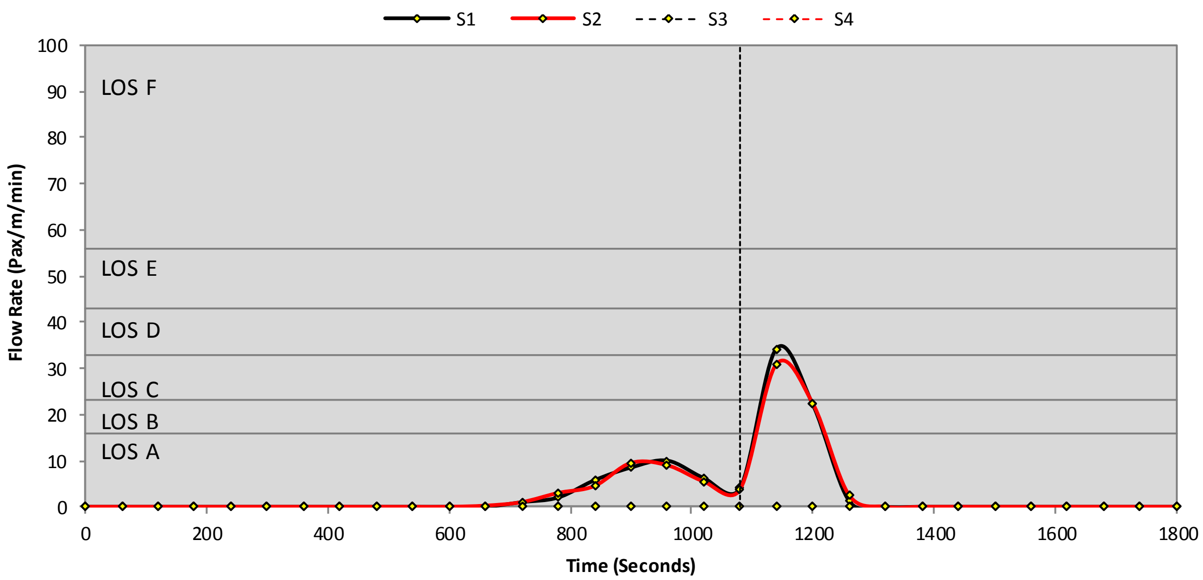
STAIR DENSITY PLOT (over length of stairs)

Plot 1: Platform 1



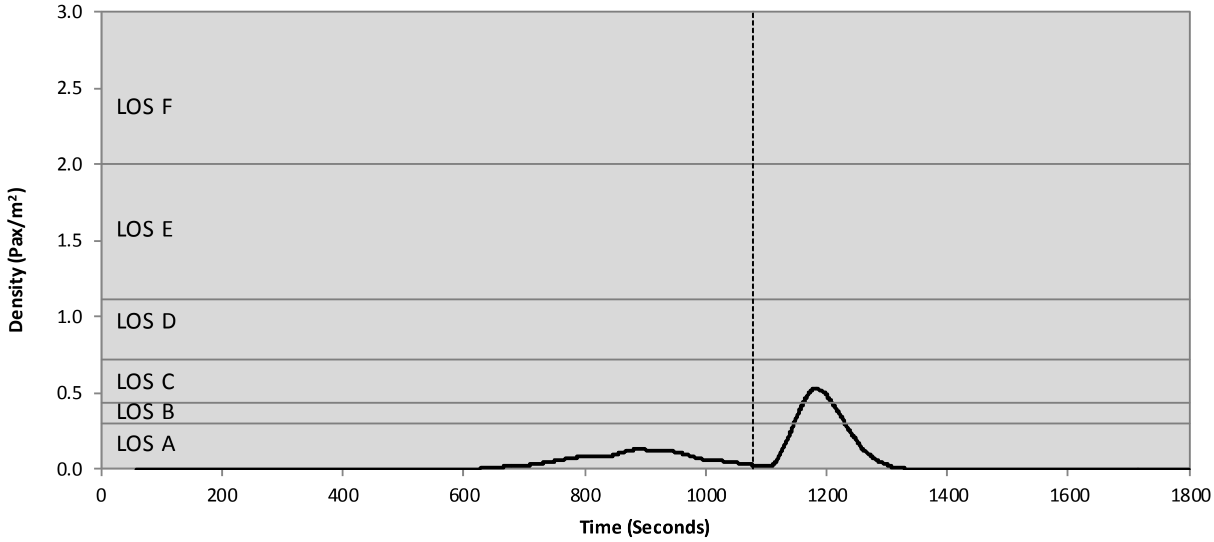
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	1647 (94.5%)	20 (1.1%)	56 (3.2%)	19 (1.1%)	0 (0%)	0 (0%)
S2 : Total Time s (%)	1649 (94.7%)	27 (1.5%)	66 (3.8%)	0 (0%)	0 (0%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

STAIR FLOW RATE PLOT (at centre of stairs)



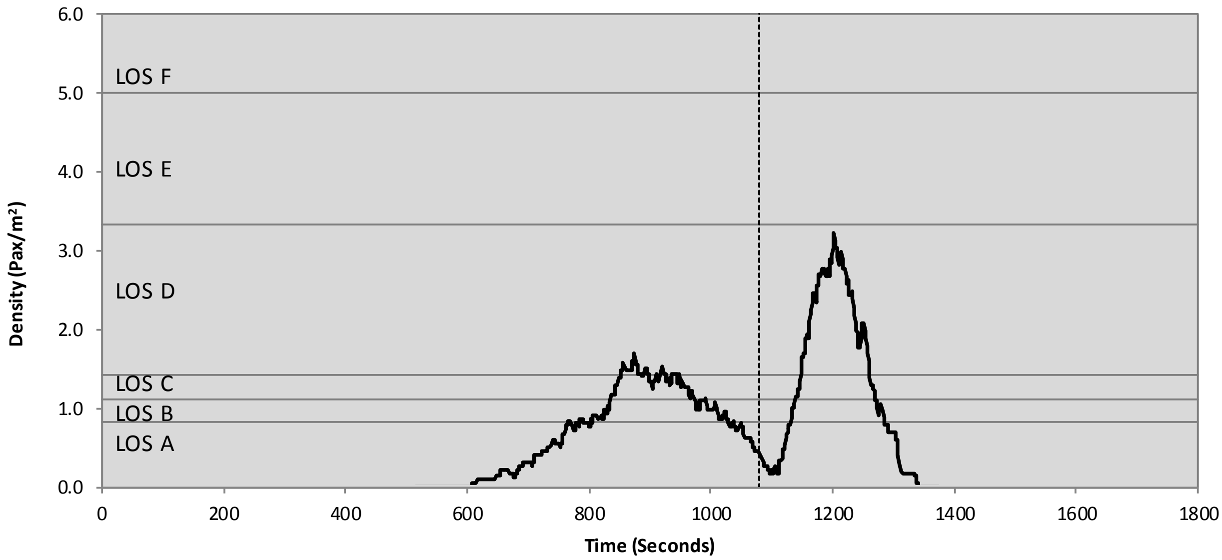
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	28 (93.3%)	1 (3.3%)	0 (0%)	1 (3.3%)	0 (0%)	0 (0%)
S2 : Total Time s (%)	28 (93.3%)	1 (3.3%)	1 (3.3%)	0 (0%)	0 (0%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

CONCOURSE DENSITY PLOT



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1716	36	48	0	0	0
Total Time in %:	95.3%	2.0%	2.7%	0.0%	0.0%	0.0%

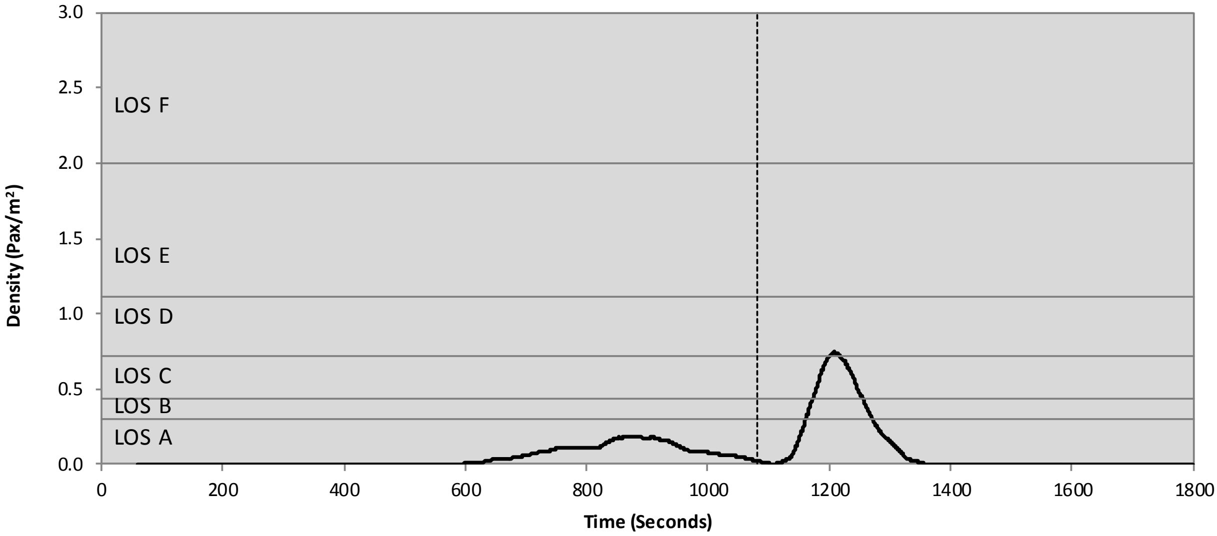
TVP QUEUE DENSITY PLOT



Total No. of TVP/Turnstiles: 4 Turnstile capacity (pax/min): 30

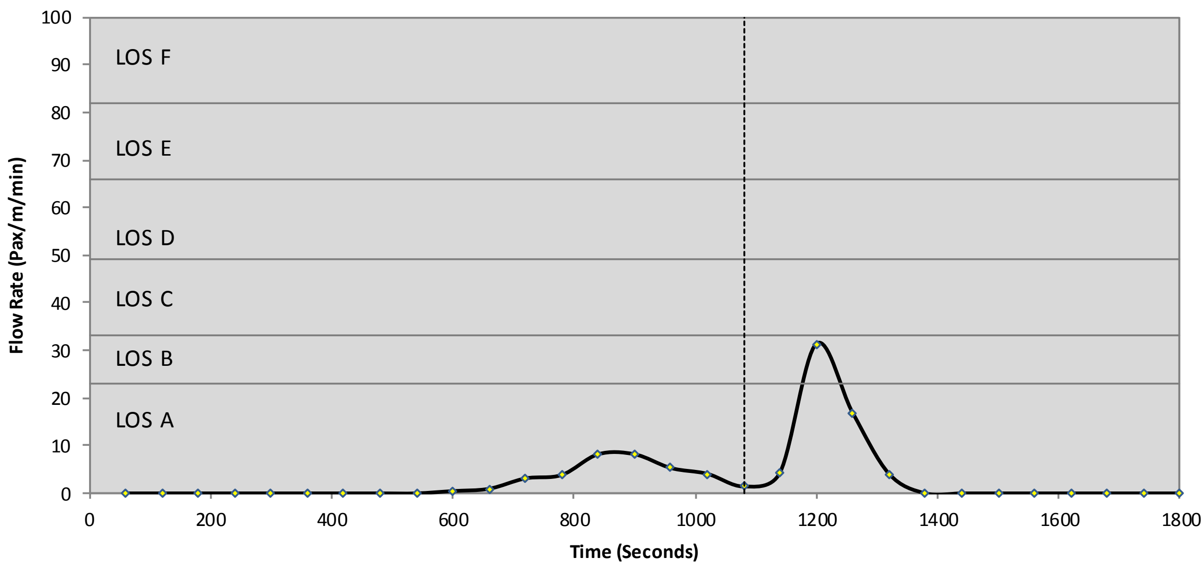
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec	1353	116	104	168	0	0
Total Time in %:	77.7%	6.7%	6.0%	9.6%	0.0%	0.0%

FOYER DENSITY PLOT



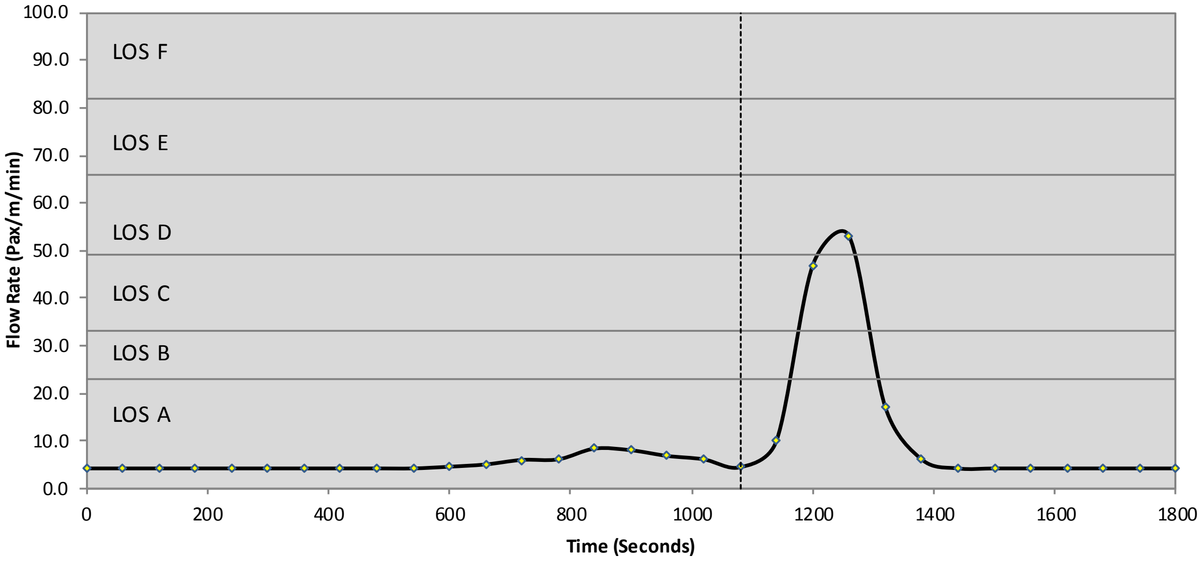
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1690	27	64	19	0	0
Total Time in %:	93.9%	1.5%	3.6%	1.1%	0.0%	0.0%

FOYER ENTRANCE FLOW RATE PLOT



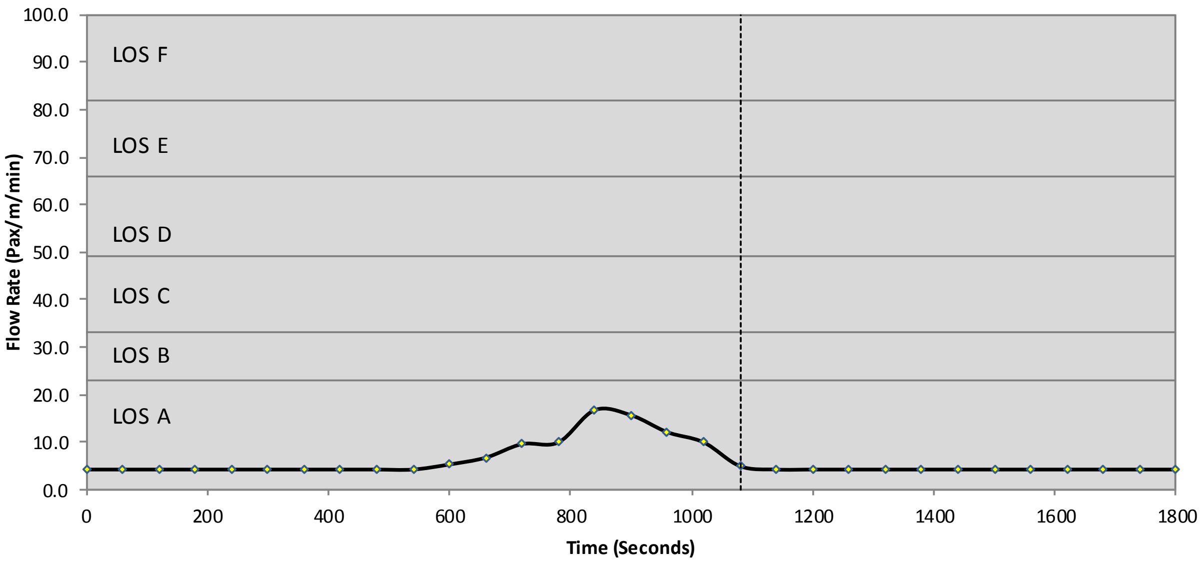
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	29	1	0	0	0	0
Total Time in %:	96.7%	3.3%	0.0%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE X): CENTURY CITY SIDE



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1680	0	120	0	0	0
Total Time in %:	93.3%	0.0%	6.7%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE Y): KENSINGTON SIDE



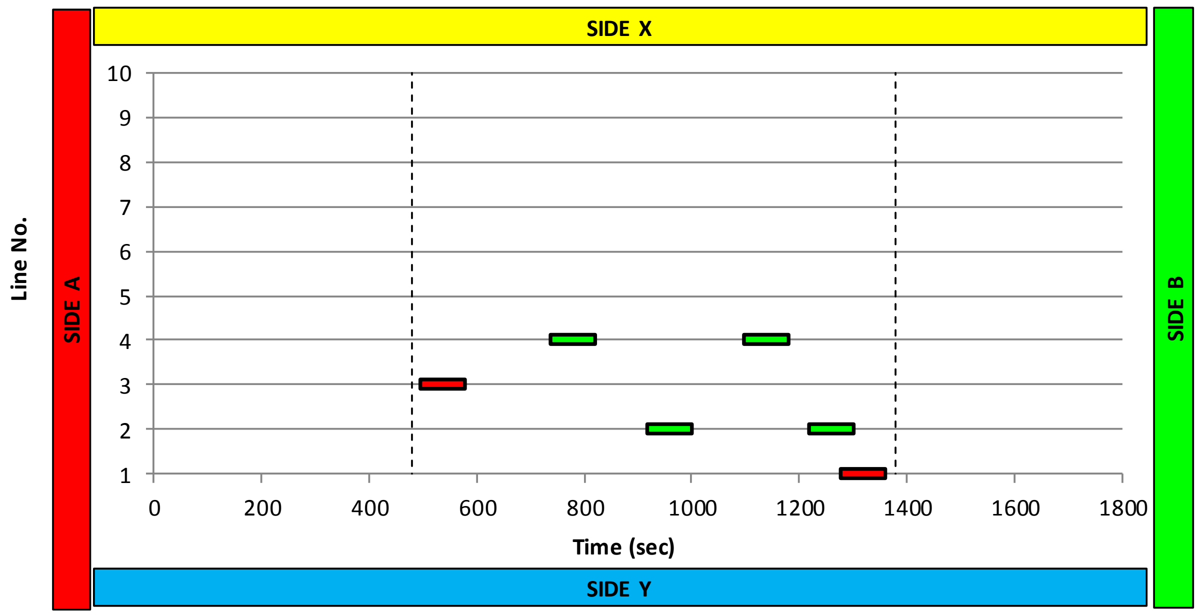
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1800	0	0	0	0	0
Total Time in %:	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

25. APPENDIX O: SP-MODEL OUTPUTS: LANGA STATION (SCENARIO 1)

TRAIN SCHEDULE AND PASSENGER VOLUMES

Train No.	Train Type	Platform	Line No.	Train Direction	Stop Arrival time (sec)	Alighting Pax	Boarding Pax	On-board Pax	Train Length	Capacity (Pax)
1	1	2	3	towards A	540	75	57	500	229.4	2604,OK
2	1	2	4	towards B	780	601	394	500	229.4	2604,OK
3	1	1	2	towards B	960	412	441	500	229.4	2604,OK
4	1	2	4	towards B	1140	362	202	500	229.4	2604,OK
5	1	1	2	towards B	1260	554	335	500	229.4	2604,OK
6	1	1	1	towards A	1320	113	98	500	229.4	2604,OK
7	0	0	0	n/a	0	0	0	0	0	
8	0	0	0	n/a	0	0	0	0	0	
9	0	0	0	n/a	0	0	0	0	0	
10	0	0	0	n/a	0	0	0	0	0	
11	0	0	0	n/a	0	0	0	0	0	
12	0	0	0	n/a	0	0	0	0	0	
13	0	0	0	n/a	0	0	0	0	0	
14	0	0	0	n/a	0	0	0	0	0	
15	0	0	0	n/a	0	0	0	0	0	
16	0	0	0	n/a	0	0	0	0	0	
17	0	0	0	n/a	0	0	0	0	0	
18	0	0	0	n/a	0	0	0	0	0	
19	0	0	0	n/a	0	0	0	0	0	
20	0	0	0	n/a	0	0	0	0	0	

TRAIN SCHEDULE



1. Colour denotes train destination for trains of similar colour.

2.All lines must carry the same colour train (denoting direction).

SITUATIONAL INPUT (PAGE 1)

Miscellaneous Details:

Name of Analyst:	L. Hermant
Station Name:	Langa
Assessment Period:	Scenario 1: AM (2025)
Date of Analysis:	02 March 2011

Station Layout Details:

Platform length, PL (m):	276.00
TVP_d (m):	157.00
Platform to Concourse height (m):	6.00
Platform MAL (m):	276.00

Platform Stair Details:

Platform No. (n):	1	2	3	4	5	6
Width/stair $S(n)_w$ (m)	2.57	2.57	0.00	0.00	0.00	0.00
$S1_t$ (m):	191.00	191.00	0.00	0.00	0.00	0.00
$S1_b$ (m):	202.00	202.00	0.00	0.00	0.00	0.00
$S2_t$ (m):	187.00	187.00	0.00	0.00	0.00	0.00
$S2_b$ (m):	176.00	176.00	0.00	0.00	0.00	0.00
$S3_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S3_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform offset $P(n)_d$ (m):	8.40	8.40	0.00	0.00	0.00	0.00
Platform width, Pw(n) (m):	9.20	9.20	0.00	0.00	0.00	0.00
Eff.Platform width,EPW (m):	3.10	3.10	0.00	0.00	0.00	0.00

Concourse Details:

Concourse width (m):	20.50	
Concourse length to TVP's (m):	35.00	
Total No. of TVP/Turnstiles:	10	(TVP: Ticket Verification Point)
Turnstile capacity (pax/min):	45	(Note: Capacity is capacity per turnstile)
Turnstile unit width (TUW) (m):	0.9	OK, Total TUW < Concourse width
Turnstile evac capacity (pax/min):	50	(evac: Evacuation capacity per turnstile)
No. Escape Gates:	1	(alongside TVP Battery)
Width of Escape Gates (m) :	1.43	
No. Bypass Gates:	1	(alongside TVP Battery)
Width of Bypass Gates (m) :	1.00	

Skywalk Details:

Skywalk width on Side X (m):	10.00	Skywalk width on Side Y (m):	10.00	Name Side X: LANGA (A)
% of Pax Boarding from Side X:	90.0%	% of Pax Boarding from Side Y:	10.0%	Name Side Y: EPPING (B)
% of Pax Alighting to Side X:	40.0%	% of Pax Alighting to Side Y:	60.0%	
Flow rate evaluation dist (Fred) (m):	23.00			
Ave. Street-to-Street Pax volume:	11	pax/min		

SITUATIONAL INPUT (PAGE 2)

Platform Emergency Details:

Platform No.:	1	2	3	4	5	6
No. Emergency Stairs:	0	0	0	0	0	0
Width/emergency stair (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of emergency stairs (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform ramp ends avail. for escape:	Side A & B	Side A & B	None	None	None	None
Width/Platform ramp end (m):	9.00	9.00	0.00	0.00	0.00	0.00
Effective width of platform ramp-ends (m):	18.00	18.00	0.00	0.00	0.00	0.00
No. Side Platform exit gates:	0	0	0	0	0	0
Width/Side Platform exit gate (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of side platform gates (m):	0.00	0.00	0.00	0.00	0.00	0.00

Foyer Details:

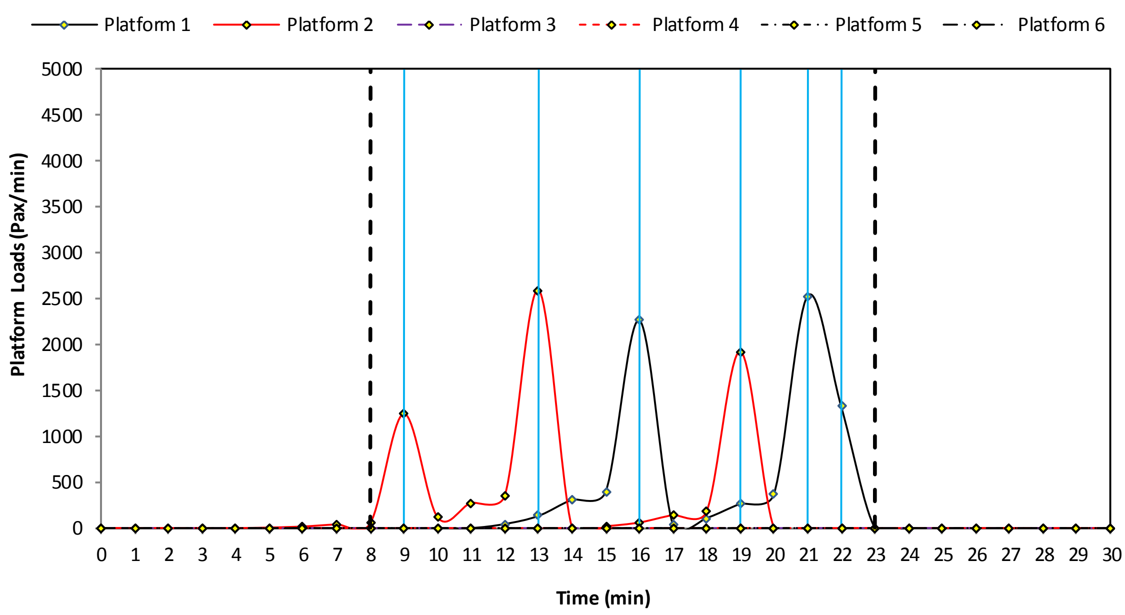
Foyer width (m):	18.00	
Foyer length to TVP's (m):	9.64	
Eff. Foyer Entrance width (m):	13.00	
No. Escape Gates:	2	(alongside Foyer Entrance)
Width of Escape Gates (m) :	1.80	
No. Bypass Gates:	0	(alongside Foyer Entrance)
Width of Bypass Gates (m) :	0.00	

Comments:

1	Empty
2	Empty
3	Empty
4	Empty
5	Empty
6	Empty
7	Empty
8	Empty
9	Empty
10	Empty

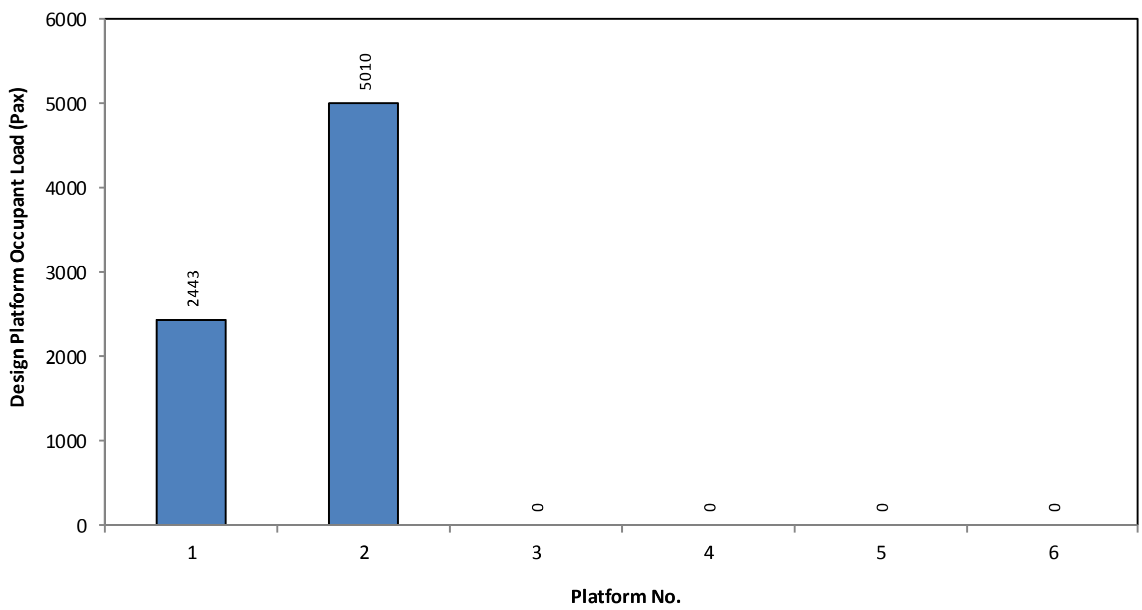
EVACUATION: LONGITUDINAL PLATFORM LOADS

Platform Loads per minute:



1. Vertical dotted lines represent extent of peak 15-min period for evacuation calculations

EVACUATION: PLATFORM OCCUPANT LOADS



Platform :	1	2	3	4	5	6	Total
Platform Occupant Load :	2443	5010	0	0	0	0	7453

EVACUATION: NFPA 130 EXITING ANALYSIS

Element	Direction	No. Units	Eff. Width (m)	Unit Capacity (pax/m/min)	Unit Capacity (pax/min)
Platform to Concourse (via Stairs)					
Stairs	Up	4	5.14	62.6	322
	Down	0	0	71.7	0
Escalators	Up	0	0	62.6	0
	Down	0	0	71.7	0
Emergency Stairs	Up	0	0.00	62.6	0
	Down	0	0	71.7	0
Platform Ramp Ends	Down	0	36.00	89.4	3218
Platform Side Gates	On Side Platforms only	0	0.00	89.4	0
				Total	3540
Concourse to Foyer (through TVP battery)					
Turnstiles		10	0.90	50	500
TVP Escape gates		1	1.43	89.4	128
TVP Bypass gates		1	1	89.4	89
				Total	717
Foyer to Safe Area (through Foyer Entrance gates)					
Foyer Entrance gates			13.00	89.4	1162
Foyer Escape gates		2	3.6	89.4	322
Foyer Bypass gates		0	0	89.4	0
				Total	1484

Walking Time for Longest Exit Route		Distance (m)	Walk Speed (m/min)	Minutes
Platform to Safe Area				
On Platform	T_1	0.00	61.00	0.00
Platform to Concourse (via stairs)*	T_2	6.00	15.24	0.39
On Concourse and foyer	T_3	52.74	61.00	0.86
Concourse to grade (via stairs)	T_4	0	71.7	0.00
On grade to safe area (via skywalk)	T_5	0.90	61.00	0.01
*: *Distance is vertical distance*			T (total walking time) = $T_1 + T_2 + T_3 + T_4 + T_5$ =	1.27

Test No. 1: Evacuate platform occupant load(s) from platform(s) in 4 minutes or less.

W_1 (time to clear platform) = $\frac{\text{Platform occupant load}}{\text{Platform exit capacity}} = \frac{7453}{3540}$ = 2.11 minutes :4 min, OI

Test No. 2: Evacuate platform occupant load(s) from most remote point on platform to a point of safety in 6 minutes or less.

W_p (waiting time at platform exits) = $W_1 - T_1$ = 2.11 minutes

Concourse occupant load = Platform occupant load - (W_1 x platform emergency exit capacity) = 677 persons

W_2 (TVP flow time) = $\frac{\text{Concourse occupant load}}{\text{TVP exit capacity}} = \frac{677}{717}$ = 0.94 minutes

W_f (waiting time at TVP's) = $W_2 - T_1$ = 0.00 minutes

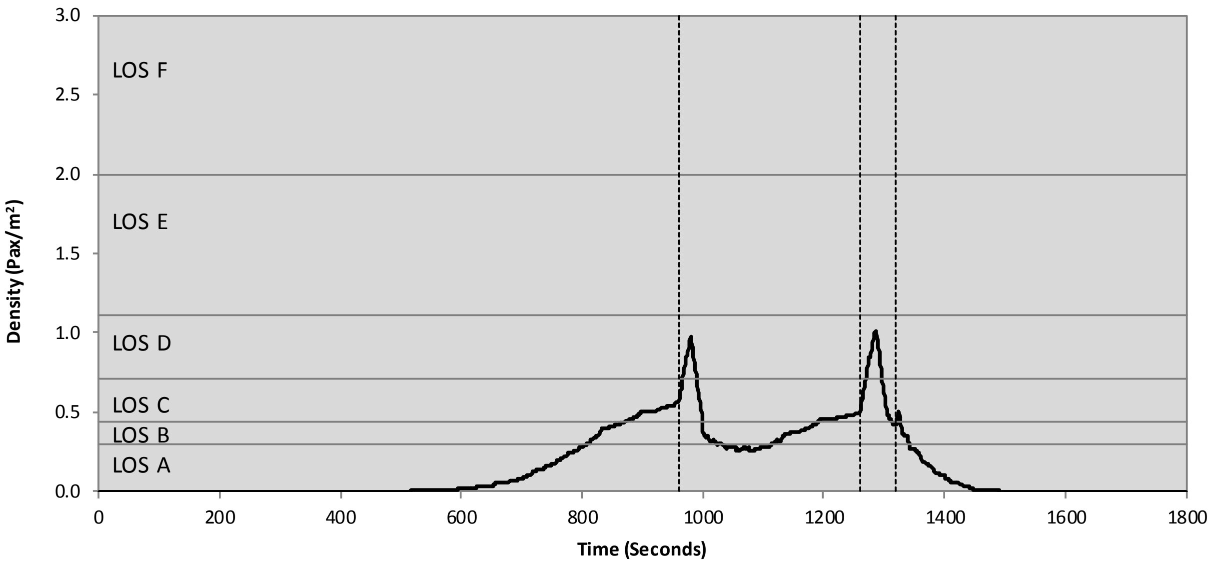
W_3 (Foyer exit flow time) = $\frac{\text{Concourse occupant load}}{\text{Foyer exit capacity}} = \frac{677}{1484}$ = 0.46 minutes

W_c (waiting time at foyer exit) = W_3 - max (W_2 or W_1) = 0.00 minutes

Total exit time = $T + W_p + W_f + W_c$ = 3.38 minutes **<6 min, OK**

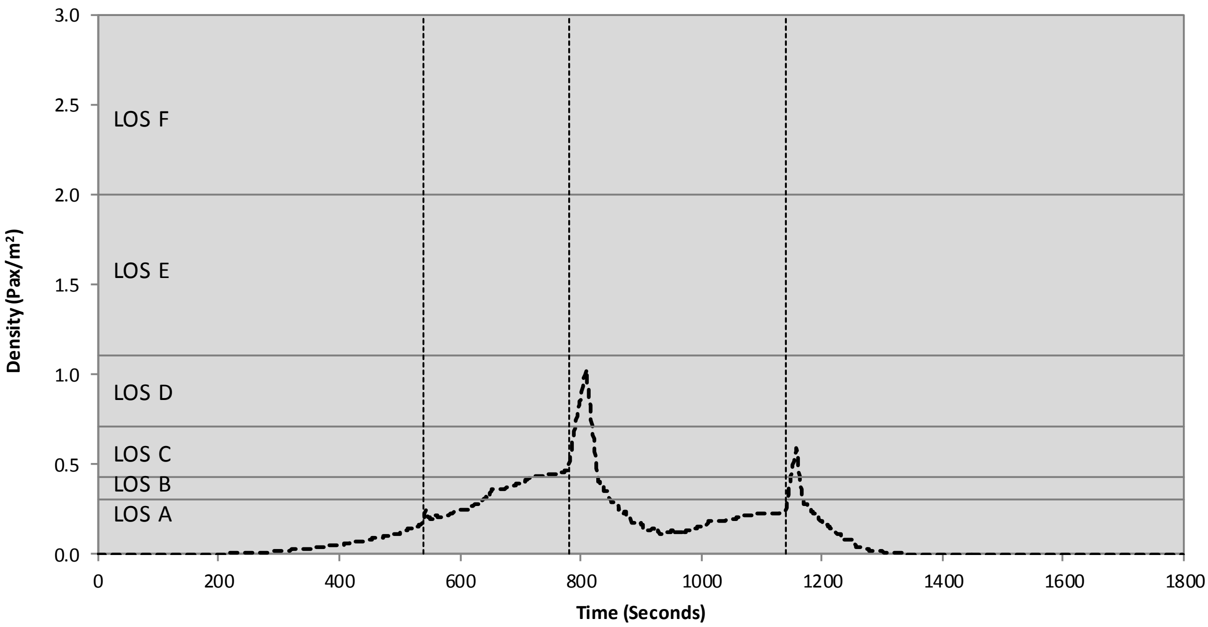
PLATFORM DENSITY PLOTS

Plot 1: Platform 1



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1364	174	213	49	0	0
Total Time in %:	75.8%	9.7%	11.8%	2.7%	0.0%	0.0%

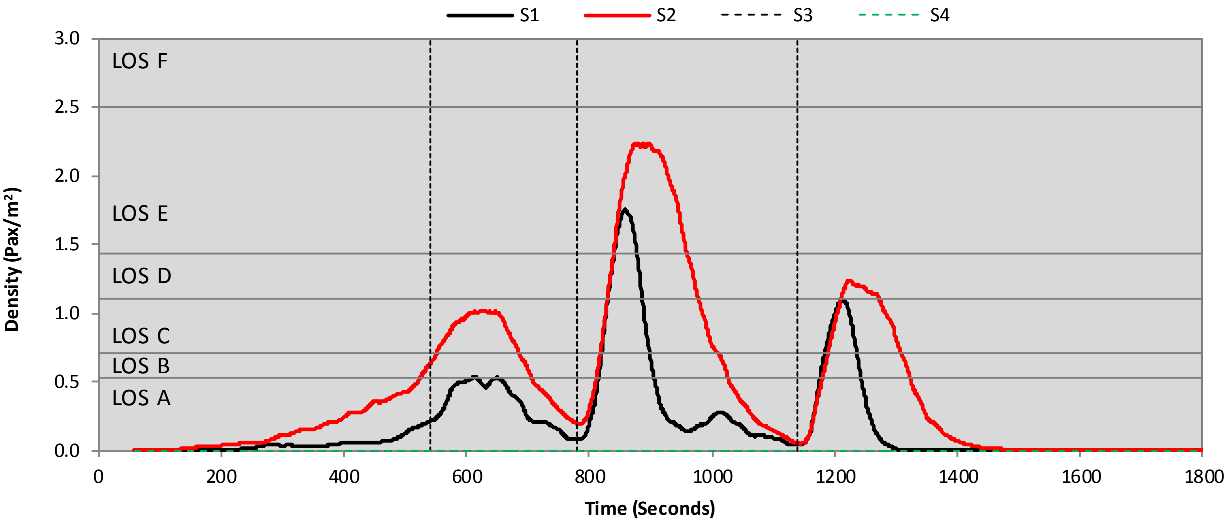
Plot 2: Platform 2



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1561	128	84	27	0	0
Total Time in %:	86.7%	7.1%	4.7%	1.5%	0.0%	0.0%

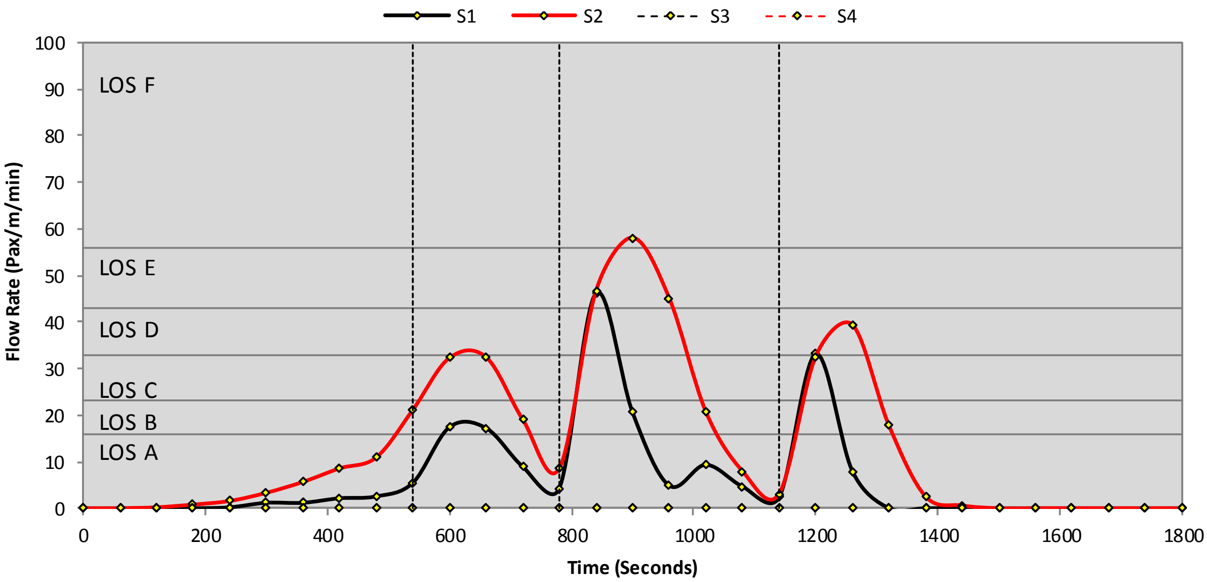
STAIR DENSITY PLOT (over length of stairs)

Plot 1: Platform 2



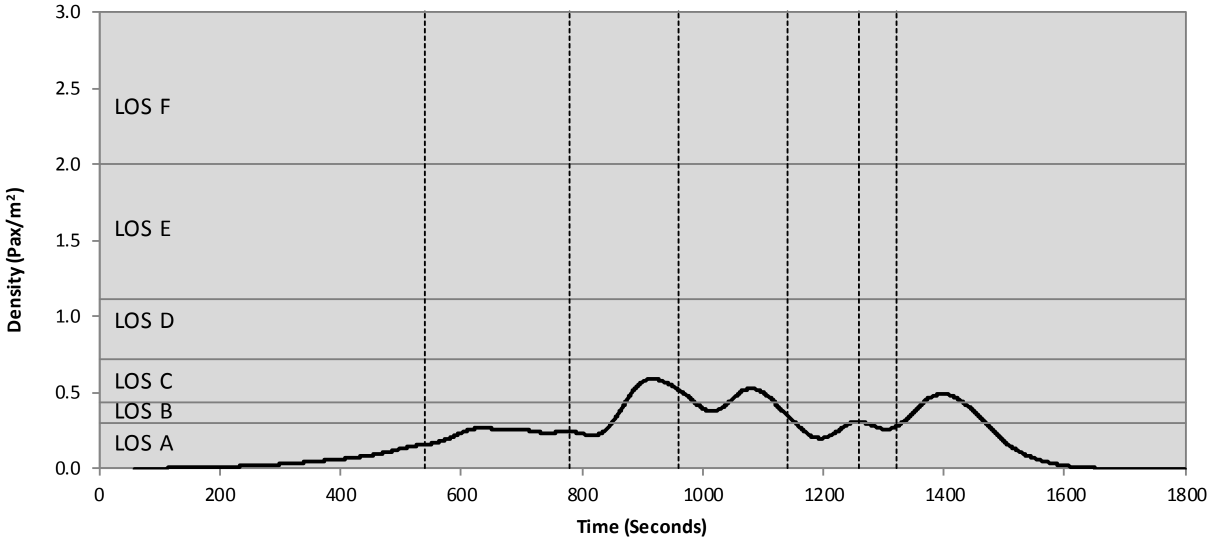
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	1568 (90%)	43 (2.5%)	75 (4.3%)	18 (1%)	38 (2.2%)	0 (0%)
S2 : Total Time s (%)	1203 (69.1%)	97 (5.6%)	232 (13.3%)	90 (5.2%)	120 (6.9%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

STAIR FLOW RATE PLOT (at centre of stairs)



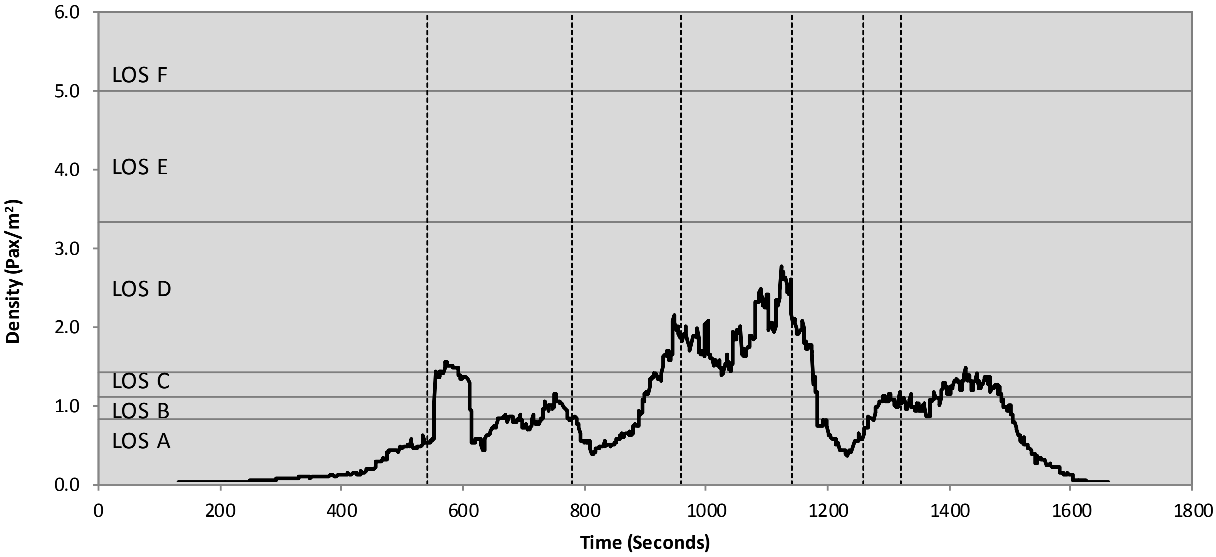
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	25 (83.3%)	3 (10%)	0 (0%)	1 (3.3%)	1 (3.3%)	0 (0%)
S2 : Total Time s (%)	19 (63.3%)	4 (13.3%)	3 (10%)	1 (3.3%)	2 (6.7%)	1 (3.3%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

CONCOURSE DENSITY PLOT



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1340	204	256	0	0	0
Total Time in %:	74.4%	11.3%	14.2%	0.0%	0.0%	0.0%

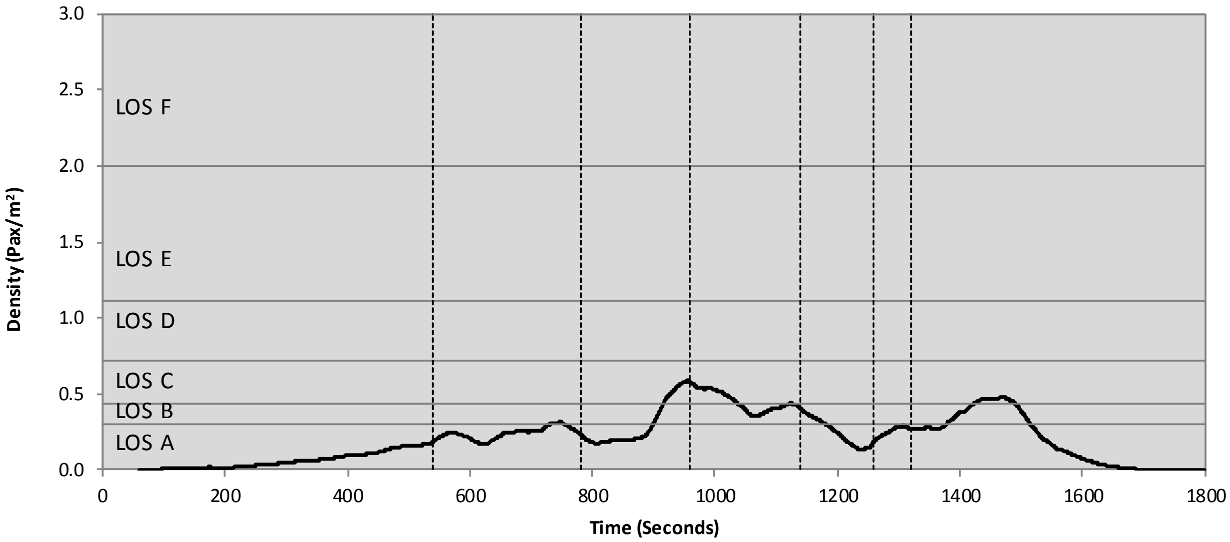
TVP QUEUE DENSITY PLOT



Total No. of TVP/Turnstiles: 10 Turnstile capacity (pax/min): 45

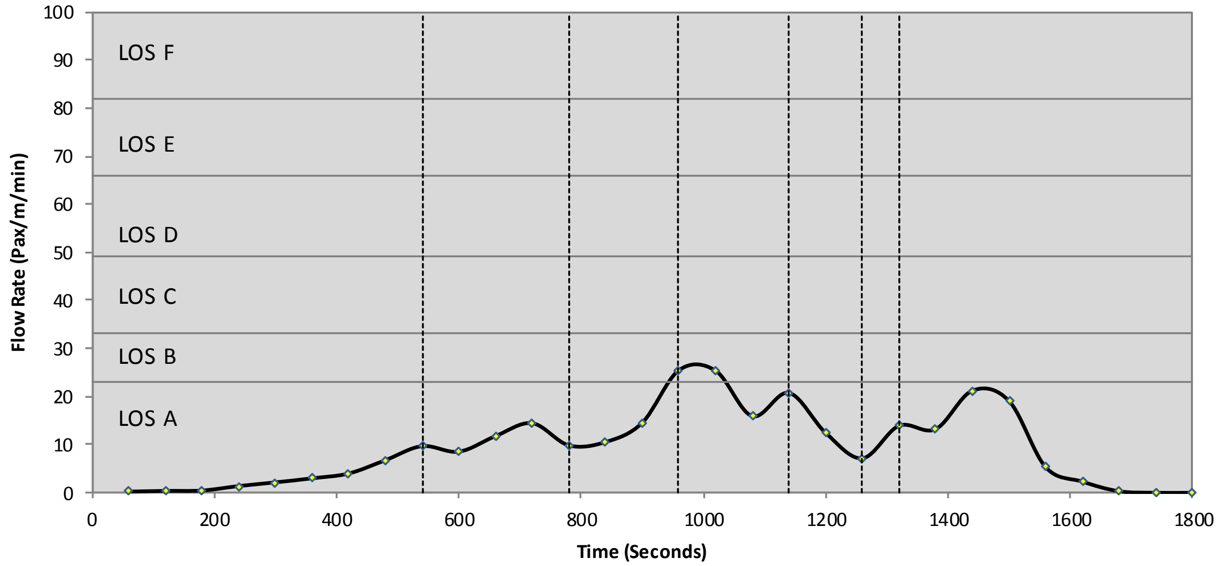
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec	1079	207	186	269	0	0
Total Time in %:	62.0%	11.9%	10.7%	15.5%	0.0%	0.0%

FOYER DENSITY PLOT



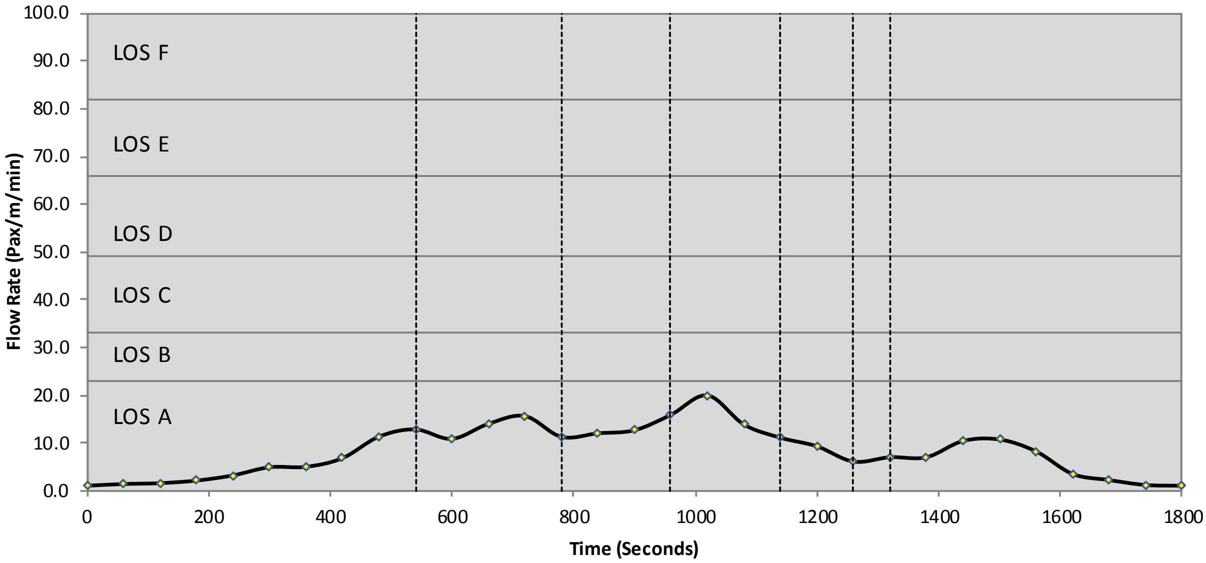
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1360	240	200	0	0	0
Total Time in %:	75.6%	13.3%	11.1%	0.0%	0.0%	0.0%

FOYER ENTRANCE FLOW RATE PLOT



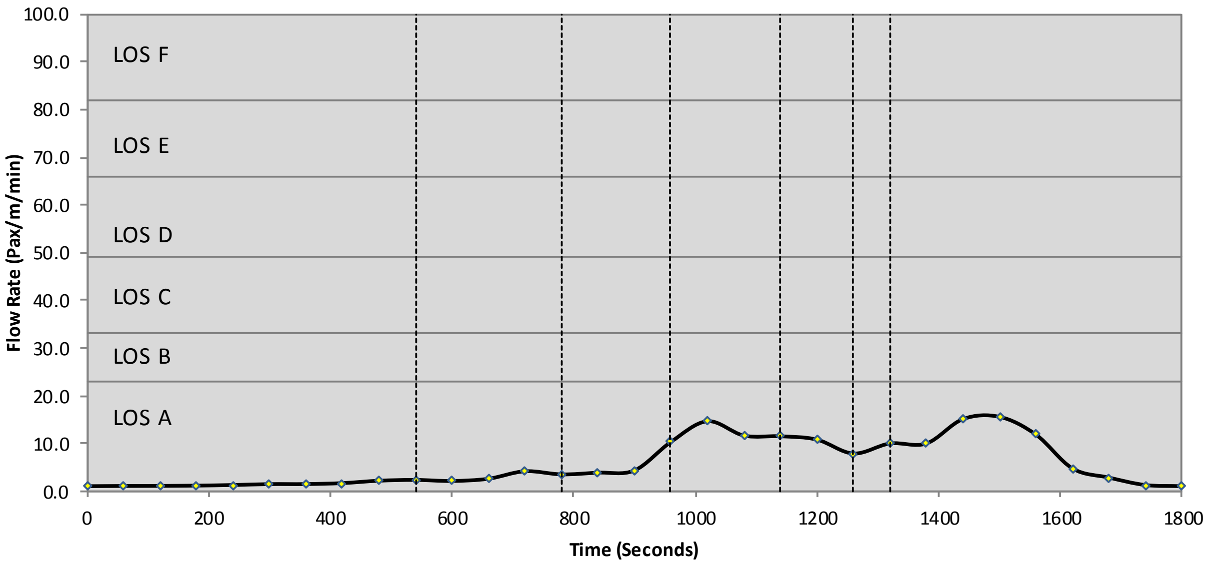
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	28	2	0	0	0	0
Total Time in %:	93.3%	6.7%	0.0%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE X): LANGA (A) SIDE



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1800	0	0	0	0	0
Total Time in %:	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE Y): EPPING (B) SIDE



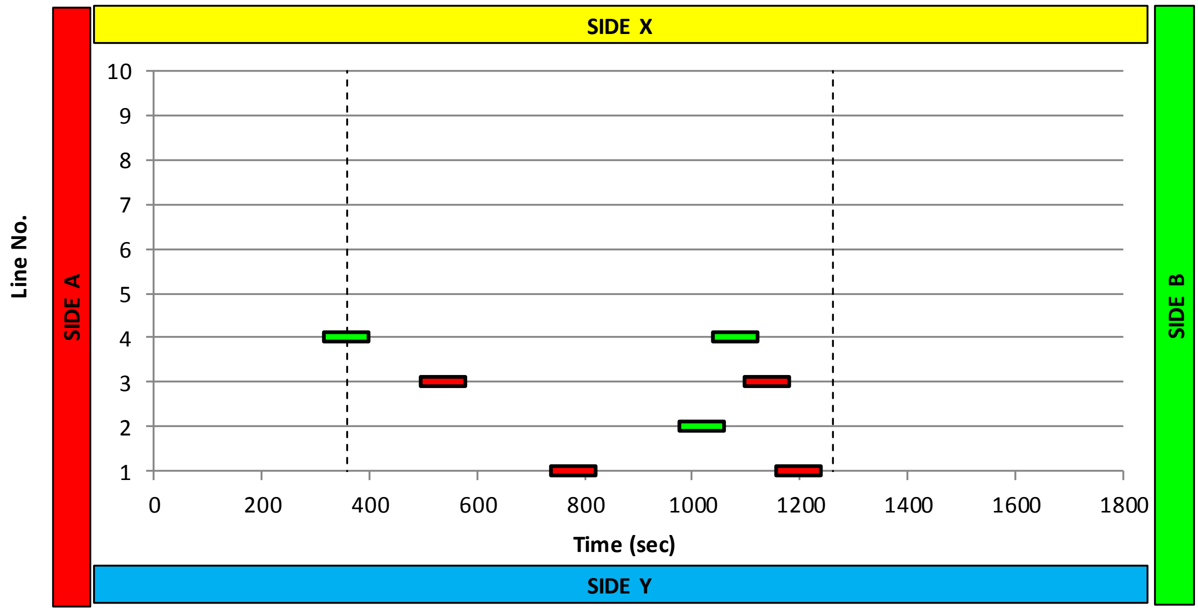
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1800	0	0	0	0	0
Total Time in %:	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

26. APPENDIX P: SP-MODEL OUTPUTS: LANGA STATION (SCENARIO 2)

TRAIN SCHEDULE AND PASSENGER VOLUMES

Train No.	Train Type	Platform	Line No.	Train Direction	Stop Arrival time (sec)	Alighting Pax	Boarding Pax	On-board Pax	Train Length	Capacity (Pax)
1	1	2	4	towards B	360	314	143	500	229.4	2604,OK
2	1	2	3	towards A	540	535	291	500	229.4	2604,OK
3	1	1	1	towards A	780	536	169	500	229.4	2604,OK
4	1	1	2	towards B	1020	345	94	500	229.4	2604,OK
5	1	2	4	towards B	1080	77	223	500	229.4	2604,OK
6	1	2	3	towards A	1140	530	514	500	229.4	2604,OK
7	1	1	1	towards A	1200	536	169	500	229.4	2604,OK
8	0	0	0	n/a	0	0	0	0	0	
9	0	0	0	n/a	0	0	0	0	0	
10	0	0	0	n/a	0	0	0	0	0	
11	0	0	0	n/a	0	0	0	0	0	
12	0	0	0	n/a	0	0	0	0	0	
13	0	0	0	n/a	0	0	0	0	0	
14	0	0	0	n/a	0	0	0	0	0	
15	0	0	0	n/a	0	0	0	0	0	
16	0	0	0	n/a	0	0	0	0	0	
17	0	0	0	n/a	0	0	0	0	0	
18	0	0	0	n/a	0	0	0	0	0	
19	0	0	0	n/a	0	0	0	0	0	
20	0	0	0	n/a	0	0	0	0	0	

TRAIN SCHEDULE



1. Colour denotes train destination for trains of similar colour.

2.All lines must carry the same colour train (denoting direction).

3. Vertical lines shows extent of pk 15-min period for evacuation.

SITUATIONAL INPUT (PAGE 1)

Miscellaneous Details:

Name of Analyst:	L. Hermant
Station Name:	Langa
Assessment Period:	Scenario 2: AM (2025)
Date of Analysis:	02 March 2011

Station Layout Details:

Platform length, PL (m):	276.00
TVP_d (m):	157.00
Platform to Concourse height (m):	6.00
Platform MAL (m):	276.00

Platform Stair Details:

Platform No. (n):	1	2	3	4	5	6
Width/stair $S(n)_w$ (m)	2.57	2.57	0.00	0.00	0.00	0.00
$S1_t$ (m):	191.00	191.00	0.00	0.00	0.00	0.00
$S1_b$ (m):	202.00	202.00	0.00	0.00	0.00	0.00
$S2_t$ (m):	187.00	187.00	0.00	0.00	0.00	0.00
$S2_b$ (m):	176.00	176.00	0.00	0.00	0.00	0.00
$S3_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S3_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_t$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
$S4_b$ (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform offset $P(n)_d$ (m):	8.40	8.40	0.00	0.00	0.00	0.00
Platform width, Pw(n) (m):	9.20	9.20	0.00	0.00	0.00	0.00
Eff.Platform width,EPW (m):	3.10	3.10	0.00	0.00	0.00	0.00

Concourse Details:

Concourse width (m):	20.50	
Concourse length to TVP's (m):	35.00	
Total No. of TVP/Turnstiles:	14	(TVP: Ticket Verification Point)
Turnstile capacity (pax/min):	45	(Note: Capacity is capacity per turnstile)
Turnstile unit width (TUW) (m):	0.9	OK, Total TUW < Concourse width
Turnstile evac capacity (pax/min):	50	(evac: Evacuation capacity per turnstile)
No. Escape Gates:	1	(alongside TVP Battery)
Width of Escape Gates (m) :	1.43	
No. Bypass Gates:	1	(alongside TVP Battery)
Width of Bypass Gates (m) :	1.00	

Skywalk Details:

Skywalk width on Side X (m):	10.00	Skywalk width on Side Y (m):	10.00	Name Side X: LANGA (A)
% of Pax Boarding from Side X:	30.0%	% of Pax Boarding from Side Y:	70.0%	Name Side Y: EPPING (B)
% of Pax Alighting to Side X:	90.0%	% of Pax Alighting to Side Y:	10.0%	
Flow rate evaluation dist (Fred) (m):	23.00			
Ave. Street-to-Street Pax volume:	9	pax/min		

SITUATIONAL INPUT (PAGE 2)

Platform Emergency Details:

Platform No.:	1	2	3	4	5	6
No. Emergency Stairs:	0	0	0	0	0	0
Width/emergency stair (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of emergency stairs (m):	0.00	0.00	0.00	0.00	0.00	0.00
Platform ramp ends avail. for escape:	Side A & B	Side A & B	None	None	None	None
Width/Platform ramp end (m):	9.00	9.00	0.00	0.00	0.00	0.00
Effective width of platform ramp-ends (m):	18.00	18.00	0.00	0.00	0.00	0.00
No. Side Platform exit gates:	0	0	0	0	0	0
Width/Side Platform exit gate (m):	0.00	0.00	0.00	0.00	0.00	0.00
Effective width of side platform gates (m):	0.00	0.00	0.00	0.00	0.00	0.00

Foyer Details:

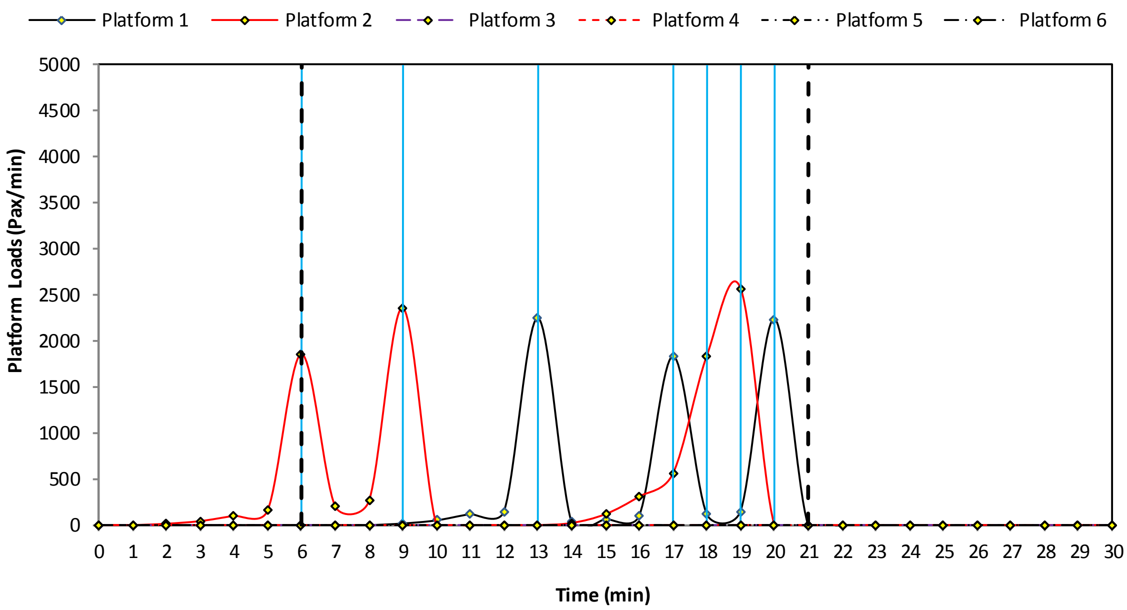
Foyer width (m):	18.00	
Foyer length to TVP's (m):	9.64	
Eff. Foyer Entrance width (m):	13.00	
No. Escape Gates:	2	(alongside Foyer Entrance)
Width of Escape Gates (m) :	1.80	
No. Bypass Gates:	0	(alongside Foyer Entrance)
Width of Bypass Gates (m) :	0.00	

Comments:

1	Empty
2	Empty
3	Empty
4	Empty
5	Empty
6	Empty
7	Empty
8	Empty
9	Empty
10	Empty

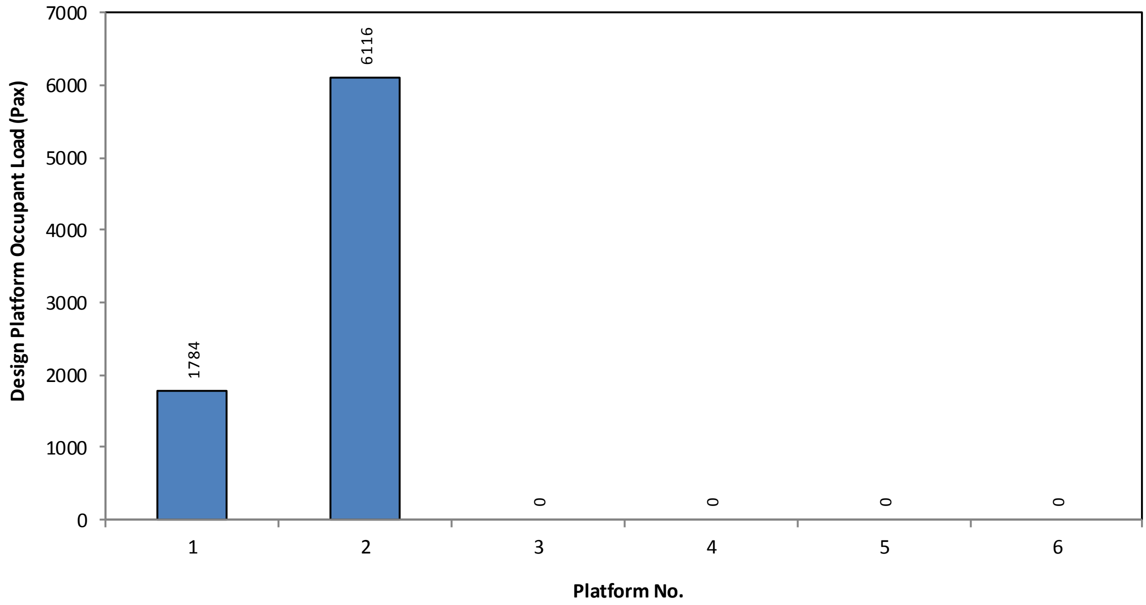
EVACUATION: LONGITUDINAL PLATFORM LOADS

Platform Loads per minute:



1. Vertical dotted lines represent ex tent of peak 15-min period for ev acuation calculations

EVACUATION: PLATFORM OCCUPANT LOADS



Platform :	1	2	3	4	5	6	Total
Platform Occupant Load :	1784	6116	0	0	0	0	7900

EVACUATION: NFPA 130 EXITING ANALYSIS

Element	Direction	No. Units	Eff. Width (m)	Unit Capacity (pax/m/min)	Unit Capacity (pax/min)
Platform to Concourse (via Stairs)					
Stairs	Up	4	5.14	62.6	322
	Down	0	0	71.7	0
Escalators	Up	0	0	62.6	0
	Down	0	0	71.7	0
Emergency Stairs	Up	0	0.00	62.6	0
	Down	0	0	71.7	0
Platform Ramp Ends	Down	0	36.00	89.4	3218
Platform Side Gates	On Side Platforms only	0	0.00	89.4	0
				Total	3540
Concourse to Foyer (through TVP battery)					
Turnstiles		14	0.90	50	700
TVP Escape gates		1	1.43	89.4	128
TVP Bypass gates		1	1	89.4	89
				Total	917
Foyer to Safe Area (through Foyer Entrance gates)					
Foyer Entrance gates			13.00	89.4	1162
Foyer Escape gates		2	3.6	89.4	322
Foyer Bypass gates		0	0	89.4	0
				Total	1484

Walking Time for Longest Exit Route		Distance (m)	Walk Speed (m/min)	Minutes
Platform to Safe Area				
On Platform	T_1	0.00	61.00	0.00
Platform to Concourse (via stairs)*	T_2	6.00	15.24	0.39
On Concourse and foyer	T_3	52.74	61.00	0.86
Concourse to grade (via stairs)	T_4	0	71.7	0.00
On grade to safe area (via skywalk)	T_5	0.70	61.00	0.01
**: Distance is vertical distance*		T (total walking time) = $T_1 + T_2 + T_3 + T_4 + T_5$ =		1.27

Test No. 1: Evacuate platform occupant load(s) from platform(s) in 4 minutes or less.

W_1 (time to clear platform) = Platform occupant load / Platform exit capacity = 7900 / 3540 = 2.23 minutes **< 4 min, OK**

Test No. 2: Evacuate platform occupant load(s) from most remote point on platform to a point of safety in 6 minutes or less.

W_p (waiting time at platform exits) = $W_1 - T_1$ = 2.23 minutes

Concourse occupant load = Platform occupant load - (W_1 x platform emergency exit capacity) = 718 persons

W_2 (TVP flow time) = Concourse occupant load / TVP exit capacity = 718 / 917 = 0.78 minutes

W_f (waiting time at TVP's) = $W_2 - T_1$ = 0.00 minutes

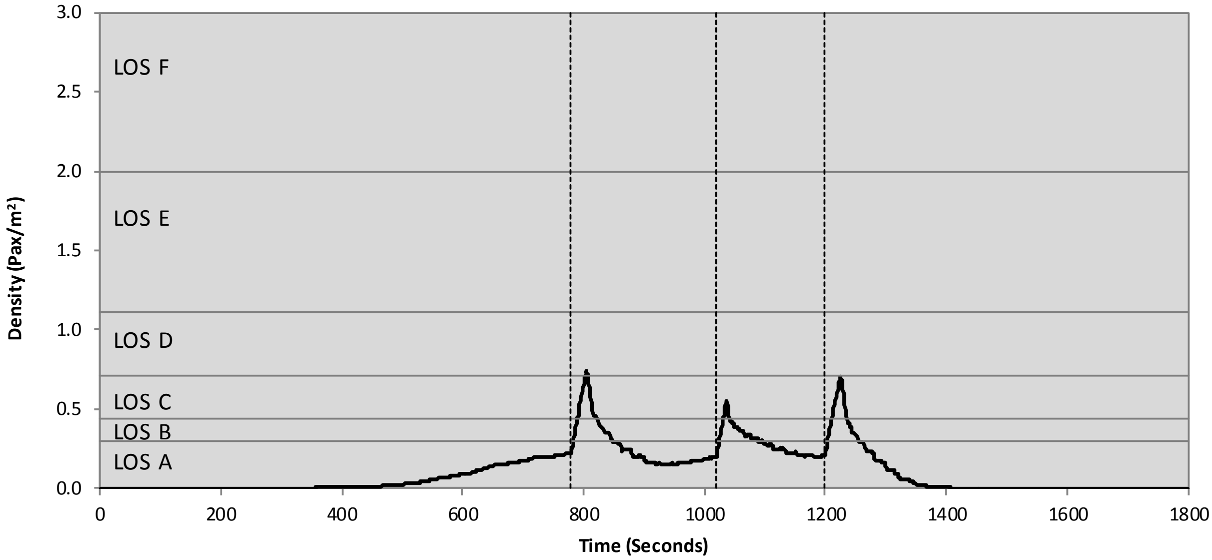
W_3 (Foyer exit flow time) = Concourse occupant load / Foyer exit capacity = 718 / 1484 = 0.48 minutes

W_c (waiting time at foyer exit) = W_3 - max (W_2 or W_1) = 0.00 minutes

Total exit time = $T + W_p + W_f + W_c$ = 3.50 minutes **< 6 min, OK**

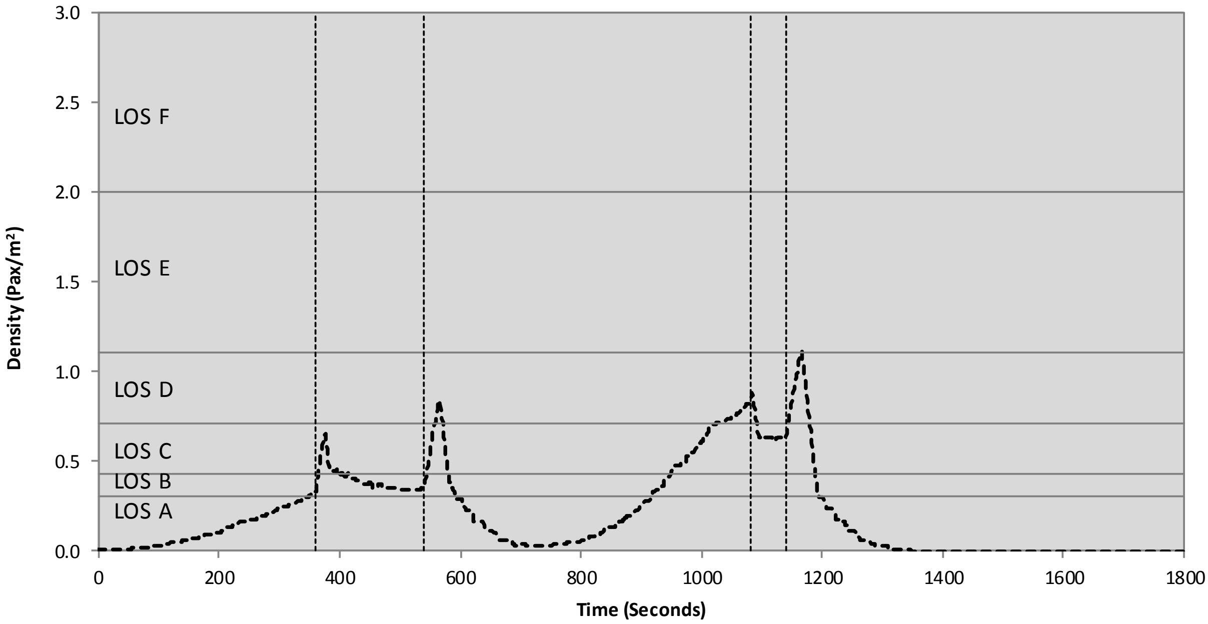
PLATFORM DENSITY PLOTS

Plot 1: Platform 1



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1622	108	66	4	0	0
Total Time in %:	90.1%	6.0%	3.7%	0.2%	0.0%	0.0%

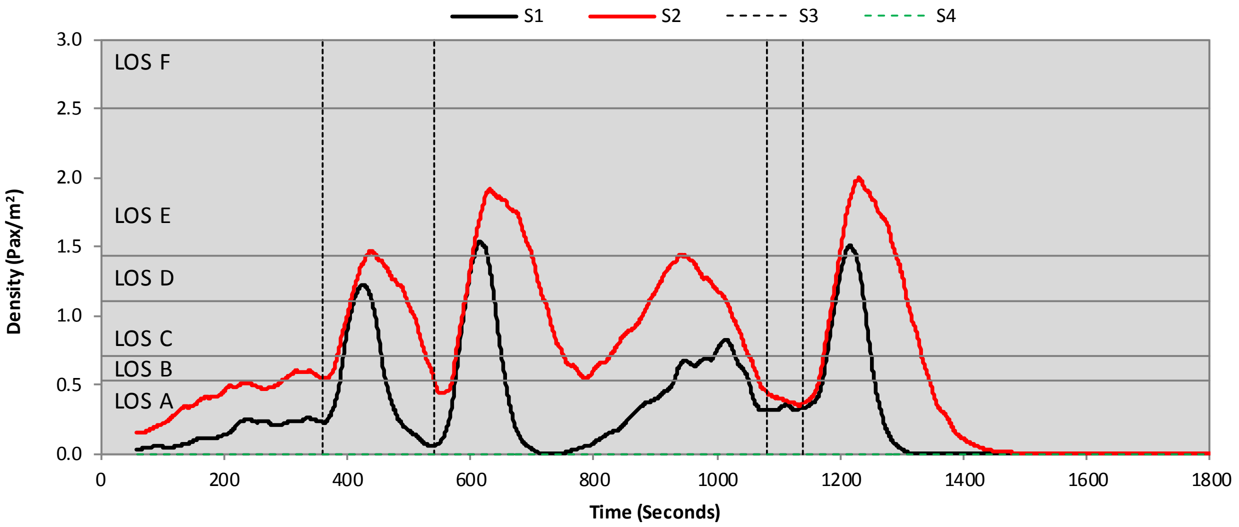
Plot 2: Platform 2



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1274	220	191	115	0	0
Total Time in %:	70.8%	12.2%	10.6%	6.4%	0.0%	0.0%

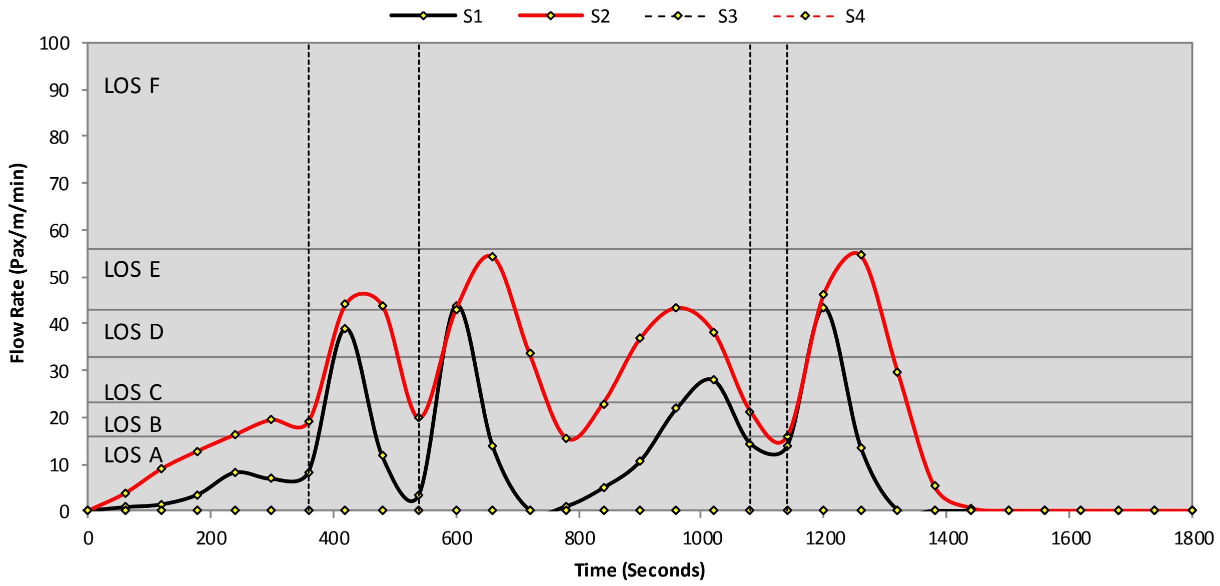
STAIR DENSITY PLOT (over length of stairs)

Plot 1: Platform 2



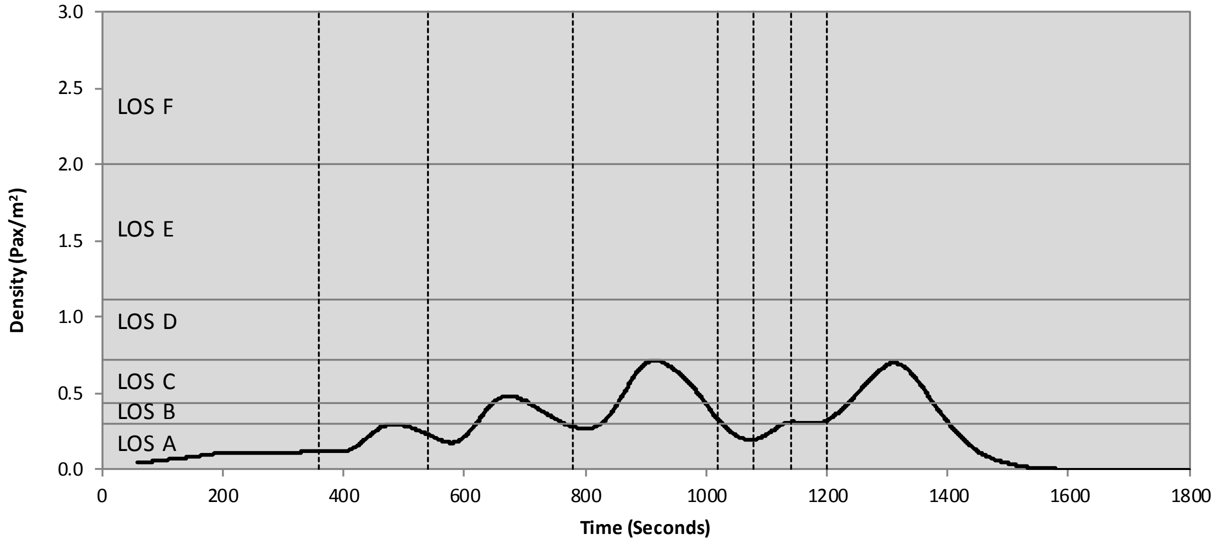
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	1379 (79.2%)	129 (7.4%)	112 (6.4%)	80 (4.6%)	42 (2.4%)	0 (0%)
S2 : Total Time s (%)	815 (46.8%)	229 (13.1%)	234 (13.4%)	244 (14%)	220 (12.6%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

STAIR FLOW RATE PLOT (at centre of stairs)



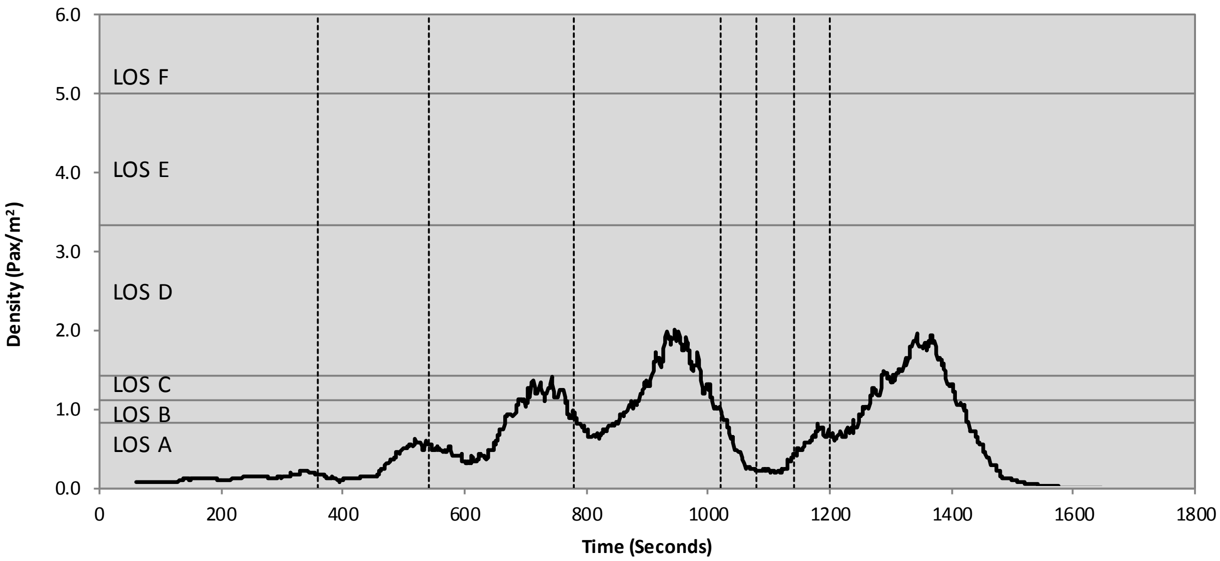
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
S1 : Total Time s (%)	25 (83.3%)	1 (3.3%)	1 (3.3%)	1 (3.3%)	2 (6.7%)	0 (0%)
S2 : Total Time s (%)	13 (43.3%)	6 (20%)	1 (3.3%)	4 (13.3%)	6 (20%)	0 (0%)
S3 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
S4 : Total Time s (%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)

CONCOURSE DENSITY PLOT



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1199	253	348	0	0	0
Total Time in %:	66.6%	14.1%	19.3%	0.0%	0.0%	0.0%

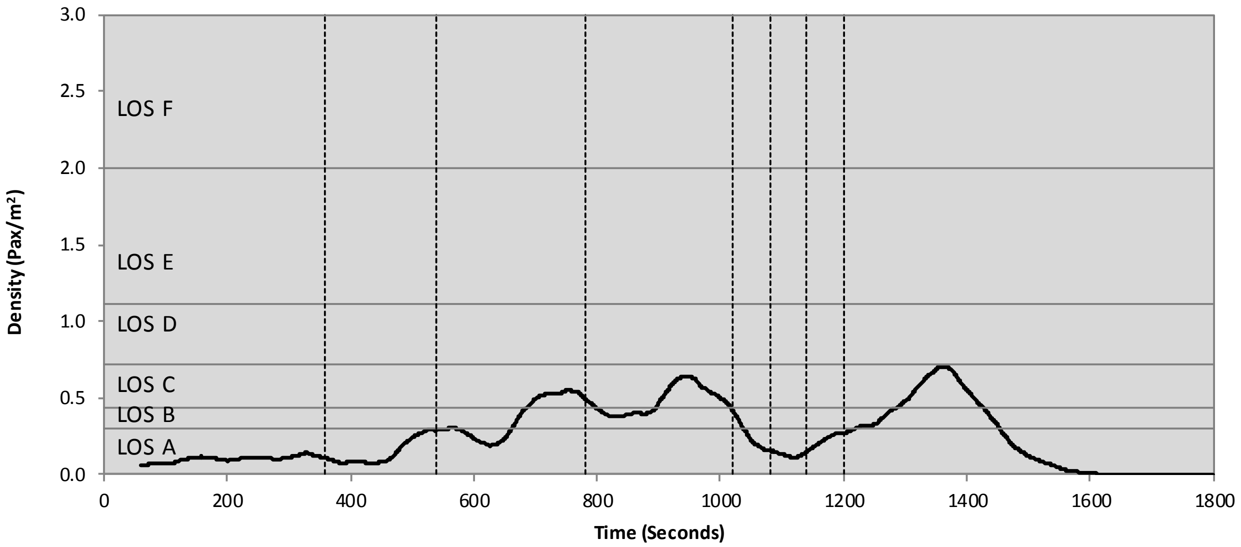
TVP QUEUE DENSITY PLOT



Total No. of TVP/Turnstiles: 14 Turnstile capacity (pax/min): 45

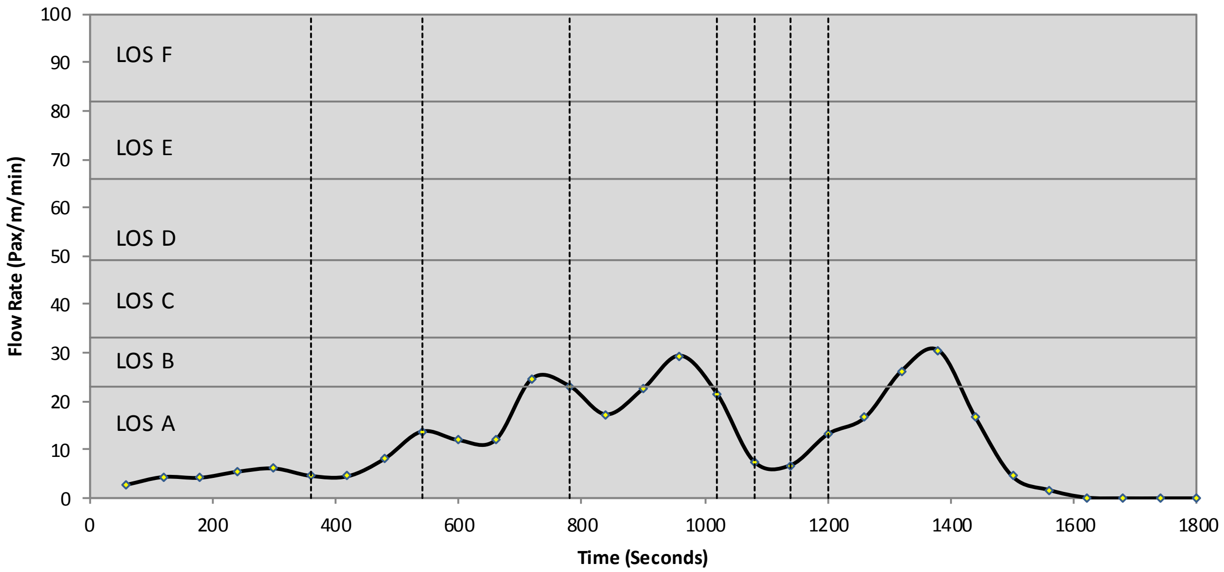
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec	1264	149	153	175	0	0
Total Time in %:	72.6%	8.6%	8.8%	10.1%	0.0%	0.0%

FOYER DENSITY PLOT



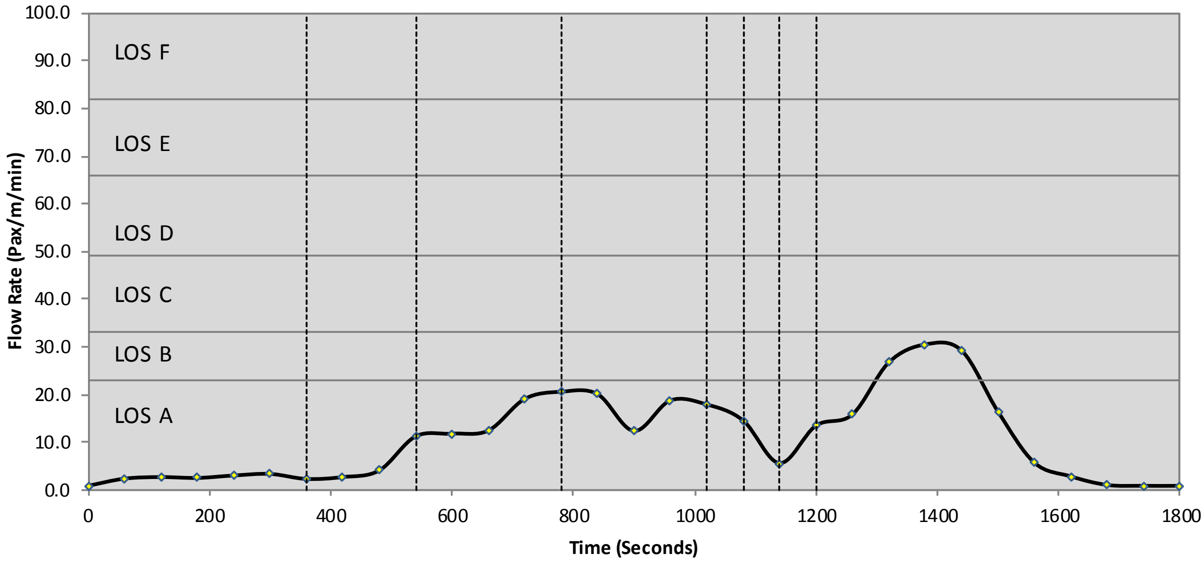
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in sec:	1181	243	376	0	0	0
Total Time in %:	65.6%	13.5%	20.9%	0.0%	0.0%	0.0%

FOYER ENTRANCE FLOW RATE PLOT



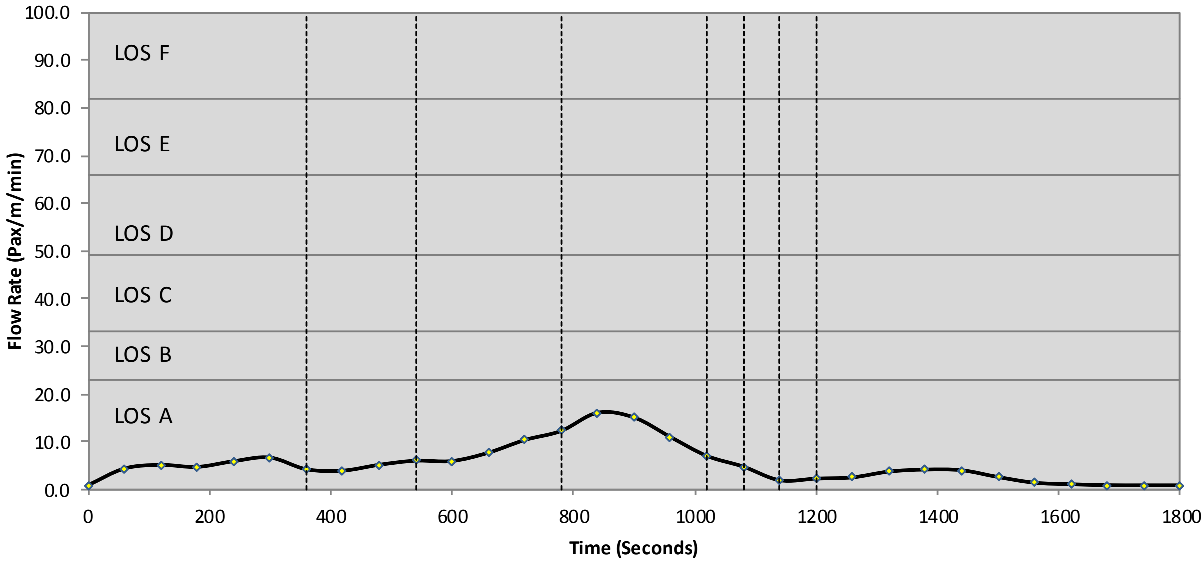
	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	25	5	0	0	0	0
Total Time in %:	83.3%	16.7%	0.0%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE X): LANGA (A) SIDE



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1620	180	0	0	0	0
Total Time in %:	90.0%	10.0%	0.0%	0.0%	0.0%	0.0%

SKYWALK FLOW RATE PLOT (SIDE Y): EPPING (B) SIDE



	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
Total Time in min:	1800	0	0	0	0	0
Total Time in %:	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%

27. APPENDIX Q: EXAMPLE OF SP-MATRIX OUTPUT: LANGA STATION

LANGA STATION : SPATIAL PARAMETERS - CENSUS 2002/CENSUS 2007 - REVISION 02 - 26 JULY 2007

ITEM	TIMEFRAME	SOURCE	CALCULATION	DESIGN VALUE	COMMENTS
Peak AM Period (Morning)	06:00 - 08:30	Census 2002 Census 2007	23292 x 1.3 30280 x 0.43	30280 Passengers both directions 13020 Passengers one direction - Alighting	The data from the 2002 Census will be used as the baseline data. Census figures from 2004 and 2007
Peak PM Hour	17:00 - 18:00 25 Trains		11208 x 1.3 14570 x 0.41	14570 Passengers both directions 5974 Passengers one direction - Alighting	are lower than 2002 due to reduced fare evasion and less rolling stock.
Peak 15 Minute Flow	17:30 - 17:45 06:45 - 07:00	Census 2002 Census 2007	3441 x 1.3 4473 x 0.48	4473 Passengers both directions 2147 Passengers one direction - Alighting 2211 Passengers both directions	Design to be based on 2025 forecast usage.
Whole Day Ratio	06:00 - 18:30	Census 2002 Census 2007	62564 x 1.3 81333 x 0.28	81333 Passengers both directions 22773 Passengers one direction - Alighting	Figures from 2002 increased by 30% for the year 2025.
Peak Percentage One Direction - Alighting Peak AM Period ÷ Whole Day Ratio		Census 2002	13020 ÷ 22773	57% Passengers one direction - Alighting	Census 2007 figures are still preliminary.
Peak 15 Minute Flow in both Directions Peak 15 Minute Flow in One Direction - Alighting Peak 15 Minute Flow in One Direction - Boarding Peak 15 Minute Flow in both Directions	17:30 - 17:45 17:30 - 17:45 17:30 - 17:45 06:45 - 07:00	Census 2002 Census 2007	4473 ÷ 15 = 298 p/min 2147 ÷ 15 = 143 p/min 1170 ÷ 15 = 78 p/min 2211 ÷ 15 = 147 p/min	300 Passengers/minute (p/min) 145 Passengers/minute (p/min) 80 Passengers/minute (p/min) 148 Passengers/minute (p/min)	
SPATIAL PARAMETERS	SOURCE	ANALYSIS	CALCULATION	DESIGN VALUE TO BE USED	LEVEL OF SERVICE
Foyer/Entrance Width AFV = Average Flow Volume AIPS = Average Inter Person Spacing	NGS Table 5.1 page 51	AFV = 33 p/m/min LOS C AIPS = 0.9 - 0.65 m LOS D	(300 ÷ 33) + 1 = 10.1 m (300 ÷ 50) + 1 = 7.0 m	10.1 m max 7.0 m min	Level of Service C Level of Service D
Foyer Area APAO = Average Pedestrian Area Occupancy	NGS Table 5.1 page 51	APAO = 0.93 - 1.21 m²/p LOS B APAO = (>1.21) m²/p LOS A	300 x 0.93 = 279.0 m² 300 x 1.21 = 363.0 m²	279 m² min 363 m² max	Level of Service B Level of Service A
Access Control Queuing in Foyer	NGS Table 5.1 page 51	APAO = 0.65 - 0.93 m²/p LOS C APAO = 0.93 - 1.21 m²/p LOS B AIPS = 0.9 - 1.0 m LOS C	(80 x 0.93 m²) + 1 = 75.4 m²	76.0 m²	Level of Service B/C
Number of Ticket Sales Points (TSP)	NGS page 53	NTSP = 15min peak x 0.0225	300 x 0.0225 = 6.8 no.	8 (including 1 default TSP)	
Ticket Sales Queuing Area	NGS Table 5.1 page 51	APAO = 0.65 - 0.93 m²/p LOS C APAO = 0.93 - 1.21 m²/p LOS B AIPS = 0.9 - 1.0 m LOS C	16p/queue x 8 TSP = 128.0 p (128 x 0.93 m²) + 1 = 120.0 m²	120 m²	Level of Service B/C
Concourse Width	NGS Table 5.1 page 51	AFV = 23 - 33 p/m/min LOS B/C AIPS = 0.9 - 1.0 m LOS C	(300 ÷ 23) + 1 = 14.0 m (300 ÷ 33) + 1 = 10.1 m	14.0 m max 10.1 m min	Level of Service B Level of Service C
Concourse Area	NGS Table 5.1 page 51	APAO = 2.33 - 3.3 m²/p LOS A+	300 x 2.33 = 699.0 m² 300 x 3.3 = 990.0 m²	699 m² 990 m²	Above Level of Service A Above Level of Service A
Access Control Queuing in Concourse	NGS Table 5.1 page 51	APAO = 0.65 - 0.93 m²/p LOS C AIPS = 0.9 - 1.0 m LOS C	(145 x 0.93 m²) + 1 = 135.9 m²	136.0 m²	Level of Service B/C
Staircase Width	NGS Table 5.1 page 51	AFV = 32 - 43 p/m/min LOS C 0.45 m each side for friction	(300 ÷ 32) + 0.9 = 10.3 m² (300 ÷ 43) + 0.9 = 7.9 m²	10.5 m max 8.0 m min	Level of Service C
Staircase Carrying Capacity	NEUFERT page 408	2.9 m wide effective staircase	2.9 x 43 p/m/min = 125 p/min 300 ÷ 125 p/min +1 = 3.4 stairs	4 stairs	Level of Service C
Turnstiles (TVP) - Current Turnstiles (TVP) - Proposed Future	NGS Document	20 p/min 40 p/min	300 ÷ 20 p/min = 15.0 no. 300 ÷ 40 p/min = 7.5 no.	16 turnstiles or 8 pairs 8 turnstiles or 4 pairs	
Turnstiles (TVP) Width	NGS Document	Length of turnstile 3 m	3m x 8 = 24 m	24.0 m	
Bypass Gates	NGS Document	1 bypass gate per 4 TVP's	8 ÷ 4 = 2 no.	2 bypass gate(s)	
Bypass Gates	NGS Document	Length of bypass gate 1.05 m	1.05m x 2 = 2.1 m	2.1 m	
Effective Width of Concourse	NGS Document	Length of gates and TVP	24.0 + 2.1 = 26.1 m	26.1 m	
Escape Routes	SABS 0400 - 1990 page 185 Table 9	160 persons maximum 1.5 m wide escape route	300 ÷ 160 = 1.9 no.	2.0 x 1.5m wide escape route(s)	